

**Future Resilient Transport Networks – Current and
Future Impacts of Precipitation on a UK Motorway
Corridor**

by

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A thesis submitted to

the University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

School of Geography, Earth and Environmental Sciences

College of Life and Environmental Sciences

University of Birmingham

June 2013

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Abstract

This thesis investigates the impact of precipitation on the UK motorway network, with the aim of determining how speed, flow and accidents are affected. Climate change impact assessments require detailed information regarding the impact of weather in the current (baseline) climate and so this thesis seeks to address gaps in knowledge of current precipitation impacts to better inform future climate impact assessments. This thesis demonstrates that whilst precipitation does impact on traffic speeds, there is no universal significant single factor relationship. Indeed, a key threshold is identified at 0 mm hr^{-1} – the fastest speeds occur when there is no precipitation and speeds immediately decrease at the onset of precipitation. More detailed findings indicate the impact can be detected in both speed and maximum flow across much of the network as well as a downward reduction in the overall speed – flow relationship. In addition to speed flow, the impact of precipitation on road traffic accidents was also investigated. Fifteen percent of accidents in the UK occur in wet weather. Precipitation related accidents are shown to have a prolonged impact on the road network and can continue to cause a decrease in traffic speed and flow for up to three hours afterwards. With increased instances of heavy precipitation predicted as a result of climate change, these findings highlight the subsequent impact on journey speeds, travel times, traffic flows and the associated economic costs.

Acknowledgments

I would like to thank my supervisors Lee Chapman and Andrew Quinn for their continued support and helping me to see the light at the end of the tunnel when things weren't going quite as planned. Thank you for all your input and encouragement which helped me make it through to the end. I would also like to thank David Jaroszweski for his help with including the findings of this research in the FUTURENET resilience modelling and the FUTURENET team for their encouragement and suggestions throughout the project.

This work was funded by EPSRC ARCC and was part of the FUTURENET project (EP/G060762). I would like to thank the Highways Agency and the IBI Group for providing the HATRIS traffic data, the UKMO (via BADC) for providing the NIMROD precipitation radar data, and the Economic and Social Data Service for providing the STATS19 data.

To my family and friends, thank you for all your help and support over the last few years. To Mike especially, thank you for encouraging me to keep going and being there to help me see it through to the end.

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List of Acronyms

BAA	British Aviation Authority
BGS	British Geological Survey
Govt.	Government
HA	Highways Agency
HATRIS	Highways Agency Traffic Information System
HRW	HR Wallingford
LA	Local Authorities
MADJ	Merged All Data Journeys
MIDAS	Motorway Incident Detection and Automatic Signalling
NR	Network Rail
OS	Ordnance Survey
SLS	Serviceability Limit State
UKCP09	UK Climate Projections 2009

Chapter 1 – Introduction

1.1 Introduction

“To date, the consequences of climate change and weather conditions have received relatively little attention. Still, it is widely known that transport systems on the whole perform worse under adverse and extreme weather conditions.”

(Koetse & Rietveld, 2009, p. 217)

It is widely accepted that weather impacts on transport, often in a negative manner (Koetse & Rietveld, 2009). Whilst previous research has sought to quantify the effects of various weather conditions on several transport modes, there are relatively few studies where impacts are considered at a local junction to junction scale. The road network is particularly susceptible to adverse weather (Andreescu & Frost, 1998; Edwards, 1998; Eisenberg, 2004; Perry & Symons, 2004) with a range of impacts when different weather conditions are experienced. Adverse weather on the road network often leads to decreases in traffic speed and flow and subsequently an increase in traffic congestion (El Faouzi *et al.*, 2010).

Precipitation is a particular hazard for the road network in the UK, due to its year round occurrence. When precipitation occurs, road surface friction, visibility and speeds are reduced and spray on the carriageway often increases. Whilst previous studies have

identified how the network may be affected by precipitation, there are few which explicitly investigate the impact of precipitation at a local scale and this thesis seeks to address this gap in knowledge. Developing a detailed knowledge of how precipitation affects the road network at a local scale is essential to keep the network fully operational throughout the year. The understanding gained from studying effects at this scale will in turn allow for improved modelling of potential future impacts, especially when considered alongside socio-economic factors which will help to shape the road network in the forthcoming decades.

1.2 FUTURENET

With some degree of climate change now inevitable (Krebs *et al.*, 2010), there is a pressing need to determine how resilient the UK's transport network is not only in its current state, but also how future resilience will be compromised or improved, taking into account changes in technology, infrastructure, demographics and climate. To assess how the transport network may be affected in future, the FUTURENET (Future Resilient Transport Networks) project aims to provide tools to assess and plan for the resilience of transport systems in future, developing understanding of how the transport network will be affected by climate. To fulfil this aim, two main questions are addressed:

- What will be the nature of the UK transport system in 2050, both in terms of its physical characteristics and its usage?

- What will be the shape of the transport network in 2050 that will be most resilient to climate change?

To answer these questions, the project considers a number of factors including meteorological and climatological studies, the effects of weather on infrastructure, possible future social scenarios, travel behaviour, and also transport modelling.

Central to the FUTURENET project is the definition of resilience. The definition used is:

“Resilience is the ability to provide and maintain an acceptable level of service in the face of challenges to normal operation.”

(Baker, 2013)

Such an approach is user-centric as the definition of an acceptable level of service differs depending on who the user is. For example, an acceptable journey delay for a business traveller is likely to be less than for a leisure traveller. Similarly, road and rail users may have different perceptions of what is an acceptable delay on each of the modes.

Whilst FUTURENET is very much focused on climate change impacts, in order to determine the future impacts of weather and climate change on transport, it is important first to understand how transport is currently affected by existing weather. Whilst the

impact of weather conditions on transport has been studied extensively, few studies investigate the impacts of weather at a local scale, particularly in the UK.

FUTURENET focuses on the transport corridor from London to Glasgow. This corridor was chosen to allow the modes of road, rail and air to be studied. The length of the corridor and the area it spans will allow for analysis of differences in climate – the warmer, drier South East and the wetter, cooler North West. Urban and rural differences along the route can also be investigated. This corridor is also of great economic importance for the UK, linking the economic heartland in London with the rest of the country. The corridor also has a number of significant sub routes which could also be studied (e.g. Birmingham to Glasgow; London to Manchester). The work detailed in this thesis seeks further to develop existing knowledge of how the motorway network within this transport corridor is currently affected by precipitation. Linkages with this wider research agenda are presented in Chapter 6.

1.3 Aim and Objectives

1.3.1 Aim

The aim of this thesis is to investigate how precipitation currently affects speed, flow and accidents on the UK motorway network. This work has been made possible by the recent availability of Highways Agency Traffic Information System (HATRIS) data. This is a new data set, of a high spatial and temporal resolution which will allow for the identification of precipitation impacts at a local scale. It permits the impacts of

precipitation to be identified at an unprecedented scale, allowing for baseline relationships to be derived which will enable the long term implications of climate change for the road network also to be considered.

1.3.2 Objectives

The objectives of this thesis are:

- To determine how precipitation currently affects speed on the UK motorway network along the M1 – M6 corridor.

Does one or more key thresholds of failure exist?

- To identify the impact of precipitation on both speed and flow at a local (junction to junction) scale.

Can traffic on the UK motorway network be approximated to the speed – flow diagram?

- To identify how accidents occurring during wet weather impact on traffic speed and flow at a local scale.

What is the impact on journey travel times? How long does the traffic stream take to recover following precipitation related accidents?

Chapter 2 - Literature Review

2.1 Introduction

Transport networks are highly valuable assets – the UK road network alone was valued as the government's single most valuable asset in 2005 with major trunk roads and motorways having an approximate value of £62 billion (Department for Transport, 2005). Understanding the impacts of precipitation on the road network both at present and in the future is of importance not only because of its regular occurrence in the UK, but also due to the extent to which it can impact on the road network, causing delays for motorists and extensive damage to infrastructure. Increased travel times caused by precipitation are not only disruptive to personal journeys but also to business journeys and the transport of freight. Disruption to journeys can have additional implications, where travellers or goods may have to reach a destination by a certain time for delivery or where further transportation is required by another mode such as sea or air. Evidently, any delays have economic repercussions and hence it is important to better understand how road transport can be affected by precipitation to better manage traffic flow and minimise delays in future.

Whilst thresholds for other weather variables and their impact on transport tend to be well defined (e.g. temperature – Chapman (2007), Dobney *et al.* (2009); wind – Baker, 2007), thresholds for precipitation, particularly on the road network, are less clear and further research is needed to identify the nature of the relationship. This chapter

examines existing literature which considers how the road network may be affected by precipitation and climate change and looks in detail at how the road network in the UK is currently affected by precipitation.

2.2 Impacts of Precipitation on the Road Network

Precipitation has been identified as the most important weather variable for road networks due to its impacts on congestion and safety (Koetse & Rietveld, 2009) and is a particular problem for the UK road network due to its year round occurrence (Edwards, 2002). Precipitation totals (and impacts) vary greatly across the UK. The driest region is the South East with annual precipitation totals of less than 600mm. In comparison, the North West has annual precipitation totals of more than 3000mm (Figure 2.1). With such large variations in precipitation it is expected that there will also be significant variation in the impacts of precipitation on the road network, reinforcing the need to determine how the network is affected at a local scale. The impact on speed and flow will vary according not only to the usage of the network but as a result of the frequency of precipitation occurring and also the intensity of the precipitation event.

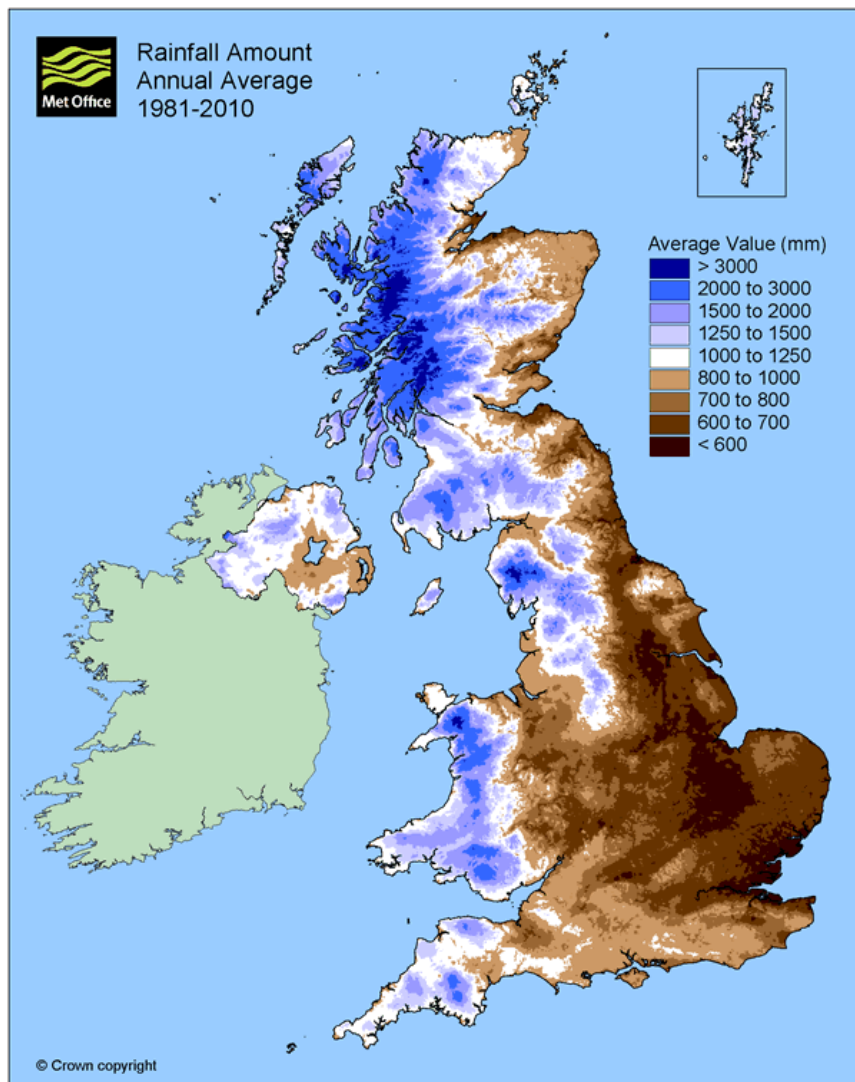


Figure 2.1 Average annual UK precipitation (Met Office, 2012)

Precipitation has several impacts on the road network, including reduced visibility and friction, as well as increasing flooding where drainage is an issue (Walsh *et al.*, 2007; Committee on Climate Change and US Transportation, 2008). Each impact will have its own relationship and associated thresholds of failure. Existing research identifies present thresholds and often highlights that these are country or even city specific. Where these thresholds are exceeded, disruption occurs and the network fails to operate

fully, with drivers often being delayed as speeds are reduced and travel times increased. Changes in precipitation patterns and intensities are likely to affect the frequency at which thresholds are exceeded and therefore affect the response of the network to precipitation in future.

Reduced visibility and friction are the most common impacts and are known to cause reductions in traffic speed. For example, Maze *et al.* (2006) discovered that when visibility was less than 0.25 miles, a 12% reduction in speed occurred in the Minneapolis / St. Paul area over a four year study period. During heavy precipitation events, visibility on the roads is severely restricted both as a result of the view through the windscreen being obscured and due to increased spray and splash from other vehicles on the road (Edwards, 2002). There are also implications for road safety with precipitation increasing the likelihood of accidents (Koetse & Rietveld, 2009).

Flooding is the most problematic and visible impact of precipitation, significantly reducing traffic speed and flows potentially to a level of total failure (closure) of some sections of the network. Recovery can be slow from such events due to damage to road surfaces and other infrastructure. Thankfully, flooding is rare and is mostly caused by prolonged rainfall which allows for some preparedness. However, flash flooding caused by extreme events is considerably more problematic. Where flooding does occur and causes sections of road to be closed, journey times are significantly increased where diversions are implemented. This can be particularly problematic where traffic has to be diverted away from high capacity roads (such as motorways or A roads) and onto lower

capacity roads which are not designed to deal with high traffic volumes, further increasing congestion and delaying journeys even more.

2.3 Extreme Precipitation Events

Past extreme weather events provide a useful starting point when investigating adverse effects and costs incurred. It is important to learn from past occurrences to be able to improve knowledge of how to deal with the occurrence of extreme weather events in the future. Extreme rainfall events quickly affect the road network with flash flooding causing a number of problems for drivers. Visibility is significantly reduced, flooding can close roads and diversions may be implemented increasing congestion and journey times. The usual impacts of precipitation for the road network are exacerbated during extreme events making driving conditions much more difficult for road users and causing much greater reductions in traffic speeds as drivers adjust their driving to cope with the adverse conditions.

On the 28th June 2012, precipitation across the UK caused chaos on the road network with many sections of road submerged by flash flooding due to the high intensity of the rainfall. There was widespread disruption with many roads grinding to a halt until the rainfall stopped, due both to water on the surface and also to the reduction in visibility making it incredibly difficult for drivers to continue their journeys (BBC News, 2012a; BBC News 2012b). With a likely increase in the number of heavy precipitation events occurring in future due to climate change, events such as this are likely to happen more

often. Without addressing the issues which arise during such events, there will continue to be adverse impacts on the network and traffic operations will be affected in a similar way in future. To reduce the impact that heavy precipitation events are likely to have, the network must adapt and infrastructure, particularly drainage, must be improved to allow the network to continue to operate effectively during such events. Lessons must be learnt from past events, using them to identify what improvements need to be made for the network to cope with similar events in future.

During particularly extreme events, motorists can be trapped where flood waters separate sections of road from the rest of the network. The Pitt Review (2008) examines the responses to the summer floods of 2007 where 10,000 motorists were trapped overnight on the M5 motorway due to flooding. Failure of the network resulting from events such as these incurs huge costs, not only in delays and repairs following the event but also in investing in adaptation measures to enable the network to be able to cope better with similar events in future. In July 2007, flooding in and around London caused lengthy delays as traffic jams built up around roads blocked by flooding (Standley *et al.*, 2009). Events such as these are widely reported because of the impact on traffic flows – indeed, the disruption to transport was the main reason that the July 2007 floods received such widespread media coverage (BBC News, 2007).

Road transport experiences extensive disruption during extreme precipitation events and this disruption will continue to occur in future as a result of extreme weather incidents (West & Gawith, 2005). Indeed, transport infrastructure is more sensitive to the effects

of changes in local climatic extremes than changes in the mean (Wilbanks *et al.*, 2007) so improved understanding of how the transport infrastructure in the United Kingdom is likely to respond to an increase in the frequency of extreme weather events is required. With the predicted increase in the number of extreme precipitation events occurring in future (Murphy *et al.*, 2009), the road network is likely to continue to be affected and in turn the ways in which authorities need to prepare for and deal with such events will also be significantly affected.

Problems on the road network during extreme precipitation clearly highlight how vulnerable the network is to the weather. Whilst lessons can be learnt from impacts during extreme precipitation events, understanding of how day to day precipitation affects the road network has to be the starting point to better manage the network during precipitation events both at present and in future.

2.4 Possible Future Impacts of Precipitation on the Road Network

The UK transport sector has already been identified as one of six key sectors which will be most affected by climate change, along with the energy; business; domestic (housing); public services; and agriculture, forestry and fisheries sectors (McKenzie Hedger *et al.*, 2000). However, there has been little attention as to how transportation may be affected by climate change and the associated extreme weather events (Ryghaug & Solli, 2012). With this in mind, it is clear that the impacts of climate change on

transport networks need careful consideration to allow the networks to continue to operate effectively in the future.

The need to mitigate the impacts of climate change is highlighted in several reports (e.g. Garnaut, 2008; The Royal Academy of Engineering, 2011) as a result of the wide range of effects that may be endured by the various transport modes. Impacts on the road network are not limited to pavements but also extend to long-term assets on the network (e.g. bridges), so it is important that adaptation strategies can be incorporated into upgrade and future development works to prevent more extensive costs in a few decades' time (Arkell & Darch, 2006). The need for flexibility in infrastructure designs to cope with the uncertainty of climate change and prevent increasing adaptation costs is identified by the UK's Adaptation Sub Committee in the '*How well prepared is the UK for climate change?*' report (Krebs *et al.*, 2010). It is unlikely that any single aspect of climate change will have a single impact on each mode. As a result, an understanding of the factors which impact on each transport mode and the corresponding infrastructure needs to be developed to allow strategies to be developed to help mitigate for and also to adapt to the potential effects.

Table 2.1 provides an overview of the predicted changes in climate, as defined by the UK Climate Projections (UKCP09), and the potential impacts of these changes on the UK road and rail transport networks. Each predicted change in climate impacts upon the transport network in several ways, and there are many consequences which need to be considered and incorporated into adaptation strategies. The issue of climate change has

been identified as ‘...the critical over-arching issue for any transport research agenda’ (Hall, 2010, p. 9). In order to understand and prepare fully for the effects of climate change on the UK road network, an integrated approach needs to be taken to further research looking at impacts across the whole of the UK. To understand how climate change may affect transport in future, it is essential to understand how current and past weather conditions impact on transport networks and infrastructure.

2.4.1 Flooding

The greatest threat of increased heavy precipitation to the road network is flooding, a problem which is likely to worsen as heavy rainfall events become more frequent and intense due to climate change (Clarke *et al.*, 2002; London Climate Change Partnership, 2005). Areas which are susceptible to flooding at present may experience more frequent flooding in future as the number of heavy precipitation events increases. It is also possible that flooding may become more extensive and as a result, larger areas may be affected in future than are currently affected unless adaptive measures are implemented. Costs to the UK transport network are likely to be substantial with the estimated cost of flood related traffic disruption on roads being at least £100,000 per hour delay on each main road affected during peak periods (Arkell & Darch, 2006). If increased heavy precipitation in the future results in more flooding events, then it is likely that these costs will increase significantly.

Table 2.1 The effects of climate change on transport

Increased numbers of hot days	<ol style="list-style-type: none"> 1. Increased thermal loading on road pavements: <ol style="list-style-type: none"> a. Melting tarmac b. Roadway buckling c. Expansion / buckling of bridges d. Increased numbers of tyre blowouts 2. Increased rail track buckling 3. Expansion / buckling of railway bridges 4. Increased heat exhaustion of maintenance and operations staff 5. Effects of lower density air on aviation: <ol style="list-style-type: none"> a. Reduced engine combustion efficiency b. Increased runway lengths required
Decreased numbers of cold days	<ol style="list-style-type: none"> 1. Reduced winter maintenance costs for road and rail 2. Improved working conditions for personnel in cold environments 3. Permafrost problems: <ol style="list-style-type: none"> a. Unable to rely on ‘frozen roads’ (essential for winter transport in polar regions) b. Infrastructure problems caused due to settlement when permafrost thaws c. Increased subsidence and landslides on slopes and embankments 4. Positive effects on marine transportation: <ol style="list-style-type: none"> a. Less de-icing required and less freezing fog b. Less ice breaking required c. Potential opening of new sea passages in polar regions 5. Reduction in icing problems for electric rail systems
Increased heavy precipitation	<ol style="list-style-type: none"> 1. Road and rail submersion and underpass flooding 2. Increased landslides and undercutting 3. Poor visibility 4. Exceedance of existing 100 year flood
Seasonal changes	<ol style="list-style-type: none"> 1. Longer summers / shorter winters will mean changes in timing of: <ol style="list-style-type: none"> a. Leaf fall for railways b. Winter maintenance regimes c. Shift in ice / snow belts 2. Reduction in frozen precipitation – significant improvements in road safety
Drought	<ol style="list-style-type: none"> 1. Navigation problems on inland waterways 2. May lead to increased failure of earthworks due to changes in the water table
Sea level change	<ol style="list-style-type: none"> 1. Locations of ports may be inappropriate 2. Other infrastructure – many airports are built 10m above sea level 3. Localised problems e.g. storm surges 4. Possible increases in coastal erosion causing problems for coastal transport routes (e.g. Dawlish railway, A55 along the north Wales coast)
Extreme events	<ol style="list-style-type: none"> 1. Increased number of tropical storms? 2. Increased lightning effects on aviation
Wind	No clear projections are available for wind

Based on Jaroszweski *et al.* (2010) and Peterson *et al.* (2008)

2.4.2 Journey Times

Current thresholds indicate that both speed and flow are reduced during precipitation, resulting in an increase in journey time. These impacts are likely to be exacerbated in future, particularly as instances of heavy precipitation increase. Traffic jams building due to obstructions on roads from flood waters will also cause journey times to increase. Efforts need to be made to improve drainage and adapt the ability of the road network to cope with increased heavy precipitation. Unless the issues with drainage and maintenance of infrastructure are addressed, the number of instances where road networks are flooded and disruption occurs will only increase. Flooding in London, for example would affect major transport interchanges (London Climate Change Partnership, 2005) with consequences not just for travellers within London but from further afield as well – both nationally and internationally. The UKCP09 projected changes in precipitation on the wettest day of the season for both winter and summer shown in Figure 2.2 indicate that, at the central estimate, there is likely to be an increase in precipitation on the wettest day during both seasons. There is extensive variability across the UK during the summer with precipitation likely to decrease more in the South than in the North, and also a greater decrease in the East than the West.

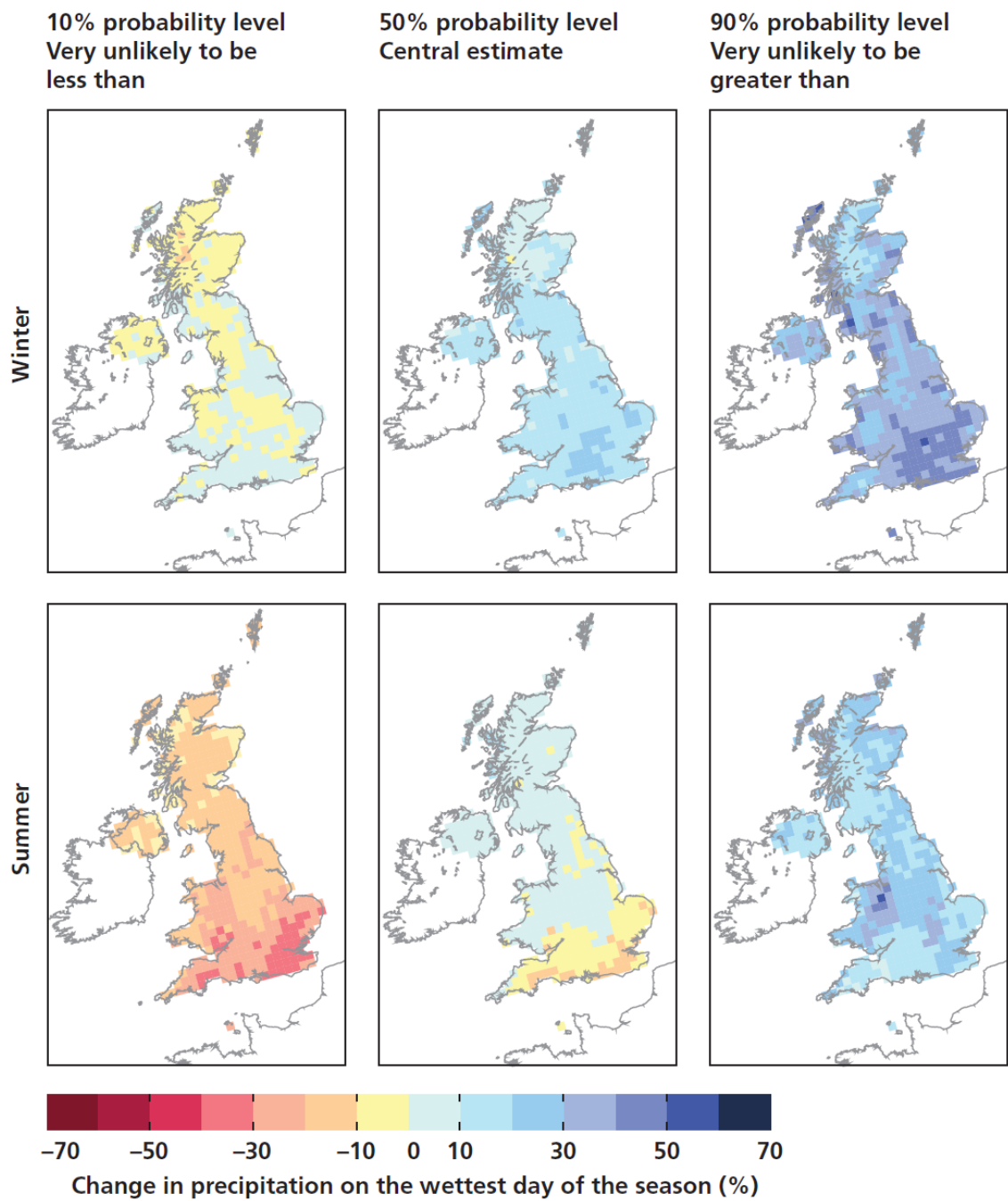


Figure 2.2 Changes to precipitation on the wettest day of the winter (top) and summer (bottom) at the 10, 50 and 90% probability levels for the 2080s under the medium emissions scenario (Murphy *et al.*, 2009)

2.4.3 Maintenance

With increased instances of heavy precipitation, it is likely that road surfaces will need to undergo increased amounts of maintenance work to repair flood damage. Flooding of road surfaces causes road scouring and road washout (Peterson *et al.*, 2008) and if these effects increase in future, then more money will have to be invested either in repairing road surfaces after flooding events have occurred, or in preventing damage – by means of improving road specifications or implementing infrastructure which will help to prevent flooding of the roads. Where roads are particularly susceptible to flooding, long term flood prevention investment may be more effective than continually repairing sections of road after each flood event.

2.4.4 Road Safety

Flooding of the road network has an adverse impact on road safety for all road users (Keay & Simmonds, 2006). Precipitation has been identified as the weather variable which has the greatest impact on road safety. Whilst higher temperatures, stronger wind speeds and occurrences of fog will all also have an adverse impact on road safety, precipitation greatly increases the likelihood of a road accident occurring (Koetse & Rietveld, 2009). As a result, an increase in the number of heavy precipitation events due to climate change prompts the need for careful consideration of the safety of the road network and measures to improve safety for road users in an attempt to reduce the number of accidents occurring when there is precipitation. There is little explicit research into what is likely to happen to congestion and road safety under climate

change and as this is an issue of great importance, it is an area which will need further research (Metroeconomica Limited, 2005 – 2006).

2.4.5 Visibility

An increase in the number of heavy precipitation events will lead to an increase in the number of instances where visibility is significantly reduced and hence will have an adverse impact on road safety. However, it is presently uncertain as to what the impact of climate change will be on fog, mist and hence visibility (Koetse & Rietveld, 2009) and so it is difficult to predict exactly how visibility will be affected and the impact this will have on road users and safety.

2.4.6 Embankment Stability

Changes in precipitation patterns and intensities will have implications for the stability of embankments on road networks. The arising problems have to be addressed to ensure that network operability is not compromised. Events such as landslips require extensive recovery work, often over prolonged time periods (Lindgren *et al.*, 2009). Previous studies have already identified that there is likely to be an increase in the failure of slopes along the motorway if no preventative measures are taken to cope with changes in slope stability as a result of climate change (Perry, 1999, in Clarke *et al.*, 2006). The risk of embankment subsidence and heave will increase due to wetter winters and drier summers (Department for Transport, 2005). Dry summer periods followed by intense precipitation events will cause significant problems and lead to landslips as

embankment materials become desiccated. This causes an alteration in structure giving the potential for landslides to occur more frequently during intense precipitation events following the drier periods (Eddowes *et al.*, 2003; Manning *et al.*, 2008). Further research is needed along specific sections of the road network where there is high usage to understand fully the implications of changes in precipitation in future for embankment stability. Findings from future research, along with improved understanding of processes affecting slope stability, will enable improved forecasting of slope stability as a result of climate change (Dijkstra & Nixon, 2010).

2.5 Existing Studies

Much of the current literature on the topic of climate change and its impacts on transport focuses on studies in the United States – for example the Committee on Climate Change and US Transportation special report into the potential impacts of climate change on US Transportation (2008). There are a handful of studies which focus on the effects of weather on transport in the United Kingdom and there are more reports emerging which examine what the potential effects of climate change may be on transport networks in the United Kingdom. However, the majority of these reports are focused on London (e.g. Arkell & Darch, 2006; Clarke *et al.*, 2002; London Climate Change Partnership, 2005).

London needs extensive consideration in any research investigating the possible impacts of climate change on UK transport as effects are likely to be exacerbated in London in

comparison to other UK cities (Clarke *et al.*, 2002). Pressure on resources in London is already high and therefore it is essential to ensure that such resources can adapt to and deal with new demands as a result of climate change. There are already several reports emerging which consider the potential impacts of climate change on London as a city, with some attention given to transport systems – for example the London Climate Change Partnership reports ‘*Climate change and London’s transport systems*’ (2005) and ‘*Wild weather warning: a London climate impacts profile*’ (2009). Reports such as these are of great value as they give a detailed insight into how transport in the capital city may be affected in future. Whilst understanding of how individual cities will be impacted is highly beneficial, it is crucial to understand how transport networks across the whole country will be affected in order to determine the resilience of the networks.

Different emission scenarios which may occur in the future as a result of changes in social responsibility, government policies and both government and individual actions produce a range of predicted changes in climate. As such, there are a range of impacts on transport which have to be assessed. It is widely recognised that weather patterns will change as a result of climate change and it is these changes which will potentially have a big impact on transport. Road networks need to be resilient to changing weather patterns to keep traffic and the economy flowing. Transport is negatively affected by heavy rain, snowfall, strong winds, extreme heat and cold, and reduced visibility, which can cause injury, damage and economic loss (Jaroszweski *et al.*, 2010; Vajda *et al.*, 2011). Hence, it is crucial to understand the potential impacts of future climate change on each transport mode in order to be able to prepare for these effects through adaptation and to provide additional adaptive capacity (Walsh *et al.*, 2007). Flooding

appears to be the most pressing issue for the road network in terms of precipitation and increased flooding instances due to increasing extreme rainfall events (Alcamo *et al.*, 2007) are a problem which require adaptation across the road network, and indeed other transport modes (McKenzie Hedger *et al.*, 2000). In order to minimise the damage to road infrastructure, adaptation measures, such as improved drainage, will have to be implemented to reduce the impacts of flooding in future. However, in order to project and model impacts via a climate change impact assessment, a clear understanding of impacts in the baseline climate is required (Jaroszweski *et al.*, 2010).

2.6 Summary

The impacts of weather and climate on all transport infrastructure have to be taken into account at the beginning of the planning stage for new transport infrastructure, and these effects need continued consideration throughout the planning process as well as during design, construction, operation and maintenance (Mills & Andrey, 2003). With this in mind, understanding the potential impacts of future climate change on the UK transport network is essential to ensure that future developments are built with sufficient resilience to the changing climate and also that existing transport networks can be adapted and modified to cope with the predicted changes. For the UK transport network to adapt to climate change, adaptation and mitigation strategies need to be built into the planning stages of new developments and incorporated into upgrades and maintenance of existing infrastructure to minimise future costs and maximise the resilience of the UK transport network over the coming years (Arkell & Darch, 2006). The response to climate change needs to be coherent across the UK to ensure that transport networks are

able to continue operating effectively across the entire country. It is not just transport infrastructure which will experience the impacts of climate change in future, there will also be changes in demand for each of the transport modes (Metroeconomica Limited, 2005 – 2006), and transport systems will have to adapt to both of these impacts to ensure their capability to continue to run as efficiently and effectively as possible.

Before future impacts of precipitation can be considered, there is a need to build on the knowledge of existing impacts particularly for those events which happen infrequently at present but may become more common in future, for example heavy precipitation events. There are a range of impacts of precipitation on the road network at present with the variation between studies highlighting the need for further research at a local level to develop a full understanding of how the network is affected. The impacts of climate change are at the forefront of research at present and there is a range of further research which is needed to develop understanding of how climate change may impact on all elements of society in future. It is only recently that the impacts of climate change on transport have begun to receive more attention, and as a result, future research in this area is of paramount importance to inform decision making, design and planning for future transport networks and infrastructure to ensure that the UK's transport networks are well equipped to cope with a changing climate.

Chapter 3 - Investigating the Impact of Precipitation on Vehicle Speeds on UK Motorways

3.1 Introduction

This chapter focuses on the impact of precipitation on the UK road network, examining how precipitation events affect traffic speeds on the motorway network, both at a route and local level. The aim is to acquire an appreciation of current impacts with a view to understanding how the UK motorway network may respond to future precipitation events within a changing climate, as well as identifying if a failure threshold for precipitation on the UK motorway exists.

3.2 Background

The key starting point in effectively assessing how precipitation affects the road network is the derivation of relationships or identification of thresholds in the current (baseline) climate. Thresholds for precipitation vary greatly between and within countries meaning a comprehensive knowledge of current impacts must be constructed to understand fully how precipitation affects the road network and its operations. Road transport has been researched in detail with studies focusing on weather impacts in a number of countries (Al-Hassan & Barker, 1999; Andrey *et al.*, 2003; Edwards, 1998; Golob & Recker, 2003). It is these existing studies which provide the background knowledge which can then be applied to develop understanding of how transport may

be affected as the climate changes. In the UK, the year round occurrence of precipitation means that it is a constant issue for the network and must be adapted to on a regular basis. A wide range of literature examining the impacts of precipitation on the road network in a number of countries can be used to inform and develop understanding of how the road network is affected. Table 3.1 provides an overview of the precipitation thresholds and relationships detected in previous studies. The variation in these thresholds is evident with a large range in reductions in both speed and capacity across countries and also within countries with a number of studies identifying that effects vary from city to city and hence there is a need for local studies to determine exactly how precipitation affects the road network at each location.

Table 3.1 Precipitation thresholds and relationships detected in the existing literature

	Author	Location	Thresholds and relationships detected
Europe	Al-Hassan & Barker (1999)	Edinburgh, Scotland	On days with rainfall – reductions in traffic activity of less than 3% on weekdays, and more than 4% on weekends
	Edwards (1998)	UK	Accidents are more frequent in wet weather than in dry weather, but are less severe
	Edwards (1999a)	Wales	Speeds are reduced slightly but significantly in wet weather
	El-Faouzi <i>et al.</i> (2010)	Europe	Speed, acceleration and traffic flow all decrease by varying levels Congestion severity increases
	Cools <i>et al.</i> (2010)	Belgium	Traffic intensity is diminished by rainfall Effects vary at each location
US and Canada	Agarwal <i>et al.</i> (2005)	Twin Cities, US	Capacity reductions vary from 10 – 17%; speed reductions vary from 4 – 7% (on days with more than 0.25 inches of rain)
	Andrey <i>et al.</i> (2003)	Canada	Precipitation is associated, on average, with a 75% increase in traffic collisions Sensitivity to weather hazards varies from city to city but cannot easily be explained
	Hranac <i>et al.</i> (2006)	Baltimore, Seattle, Minneapolis, St. Paul, US	Speed at capacity reduced by between 8% and 14% Free flow speed reduced by between 3% and 9%
	Ibrahim & Hall (1994)	Mississauga, Canada	Free flow speeds reduced by 5 – 10 km h ⁻¹
	Martin <i>et al.</i> (2000)	Utah, US	Speeds reduced by 10% in wet weather
	Maze <i>et al.</i> (2006)	Minneapolis St. Paul, US	Speeds reduced by up to 10% in wet weather
	Smith <i>et al.</i> (2004)	Virginia, US	Capacity and speed both affected: reduction in speed of 5 – 6% during precipitation Journey times and traffic congestion increase significantly during precipitation

3.3 Method

3.3.1 Study Area

This chapter analyses the route corridor from Staples Corner in north London to 10 km south of the England – Scotland border. The corridor starts at Junction 1 of the M1 and follows the M1 to Junction 19 (Catthorpe Interchange at Rugby) then the M6 to Junction 44, as shown in Figure 3.1. Such an extensive cross country route is important to allow for future analysis of differences between climates and between urban (e.g. Birmingham – M6 junctions 4 to 11) and rural (e.g. The Lake District – M6 junctions 36 – 40) sections of motorway and the impacts that may occur in these locations.

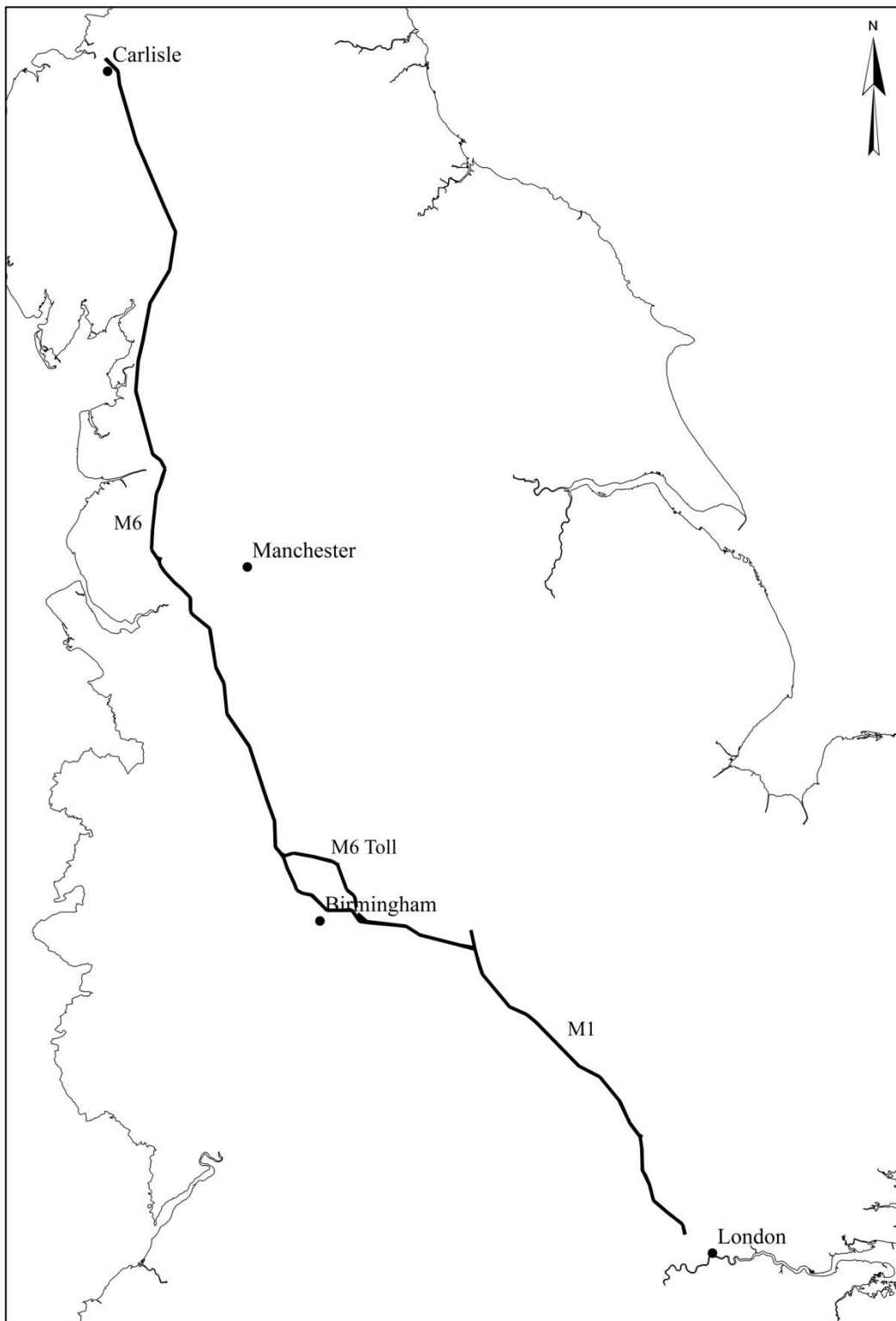


Figure 3.1 Study corridor – London to Carlisle (via M1 and M6)

3.3.2 HATRIS Data

The Highways Agency Traffic Information System (HATRIS) systematically monitors traffic flow and vehicle speeds across the road network. Information is collected from a number of sources including cameras installed on the motorway network, loops installed in the road surface and vehicles fitted with tracking devices. The main sources of data along the route corridor are MIDAS (Motorway Incident Detection and Automatic Signalling), Trafficmaster, NTCC (National Traffic Control Centre), and ITIS (data from ITIS Holdings plc). Each system records traffic flow and travel time across the motorway links using a different methodology and all are incorporated into the HATRIS database to provide as much information as possible about the network. Therefore HATRIS is a rich, high resolution dataset containing speed and flow information for all motorway links across England and Wales. Links are defined as junction to junction sections of the motorway and there are approximately 2500 which make up the entire motorway network. The route corridor in this thesis comprises 146 operational junction to junction links. Included in the database are details of speed, journey times and traffic flows which can be used for analysis. Significant alterations in the data which correlate with the occurrence of different weather events, in particular extreme weather events will be identified in this study. The variables available for analysis are detailed in Table 3.2.

Table 3.2 Variables available for analysis in the HATRIS data set (based on Hardman, Dickinson & Frith, 2007)

Variable Name	Variable Description
Rref	Unique link ID
travelDate	Date of travel
dayTypeID	Day type that the day belongs to, defined by whether the day is a weekday, weekend, bank holiday, school holiday etc
timePeriodID	One of 96 fifteen minute time periods throughout the day
MADJ_avgJT	'Best of 3 sources' Merged All Data Journeys estimate of average journey time (seconds) to travel across the link during the 15 minute time period
MADJ_avgSpeed	'Best of 3 sources' MADJ estimate of average speed (km h ⁻¹) across the link during the 15 minute time period (Calculated using (length / MADJ_avgJT))
MADJ_qualityIndex	'Best of 3 sources' MADJ quality index – High, Medium or Low (taken from source used)
MADJ_JTdataType	'Best of 3 sources' MADJ data type – indicates whether data is observed or has been infilled from another source
MADJ_avgrowsV	'Best of 3 sources' MADJ vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
MADJ_avgRowsH	'Best of 3 sources' MADJ horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)
MADJ_dataSource	Source of the travel time data: MD = MIDAS; TM = Trafficmaster; IT = ITIS; FF = freeflow (Indicates that there is no observed or infilled data from any of the 3 sources)
MD_avgJT	MIDAS estimate of average journey time (seconds) to travel across the link during the 15 minute time period, calculated from loops on the network
MD_avgSpeed	MIDAS estimate of average speed (km h ⁻¹) across the link during the 15 minute time period (Calculated using (length / MD_avgJT))
MD_qualityIndex	MIDAS quality index – High (no data infilling, more than 1 loop per 1000m), Medium (more than 1 loop per 1000m) or Low (criteria for medium quality not met)
MD_JTdataType	MIDAS data type – indicates whether data is observed or has been infilled from another source
MD_avgRowsV	MIDAS vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
MD_avgRowsH	MIDAS horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)
TM_avgJT	Trafficmaster estimate of average journey time (seconds) to travel across the link during the 15 minute time period
TM_avgSpeed	Trafficmaster estimate of average speed (km h ⁻¹) across the link during the 15 minute time period (Calculated using (length / MADJ_avgJT))
TM_qualityIndex	Trafficmaster quality index – High (average sample size > 5, minimum sample size > 0, no infilling of data), Medium (average sample size > 5, minimum sample size > 0) or Low (criteria for medium quality not met)
TM_JTdataType	Trafficmaster data type – indicates whether data is observed or has been infilled from another source
TM_avgRowsV	Trafficmaster vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
TM_avgRowsH	Trafficmaster horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)

IT_avgJT	ITIS estimate of average journey time (seconds) to travel across the link during the 15 minute time period
IT_avgSpeed	ITIS estimate of average speed (km h^{-1}) across the link during the 15 minute time period (Calculated using $(\text{length} / \text{IT_avgJT})$)
IT_qualityIndex	ITIS quality index – Medium (no infilling of data, average car sample >2, average HGV sample > 2, minimum sample > 0) or Low (criteria for medium quality not met)
IT_JTdataType	ITIS data type – indicates whether data is observed or has been infilled from another source
IT_avdRowsV	ITIS vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
IT_avgRowsH	ITIS horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)
TG_avgJT	Estimate of average journey time (seconds) to travel across the link during the 15 minute time period
TG_avgSpeed	Estimate of average speed (km h^{-1}) across the link during the 15 minute time period (Calculated using $(\text{length} / \text{MADJ_avgJT})$)
TG_qualityIndex	Quality index – High, Medium or Low
TG_JTdataType	Data type – indicates whether data is observed or has been infilled from another source
TG_avgRowsV	Vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
TG_avgRowsH	Horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)
NT_avgJT	NTCC estimate of average journey time (seconds) to travel across the link during the 15 minute time period
NT_avgSpeed	NTCC estimate of average speed (km h^{-1}) across the link during the 15 minute time period (Calculated using $(\text{length} / \text{NT_avgJT})$)
NT_qualityIndex	NTCC quality index – based on ratio of distance between cameras and link length: High (ratio at least 0.75 and no infilling of data), Medium (not High or Low quality) or Low (ratio less than 0.25 and over 50% of data infilled)
NT_JTdataType	NTCC data type – indicates whether data is observed or has been infilled from another source
NT_avgRowsV	NTCC vertical row values – average number of records used for vertical infilling (0 indicates that observed data is used)
NT_avgRowsH	NTCC horizontal row values – average number of records used for horizontal infilling (0 indicates that observed data is used)
FF_avgJT	Free flow journey time (seconds)
FF_avgSpeed	Free flow speed (km h^{-1}) calculated using $\text{length} / \text{FF_avgJT}$
FF_qualityIndex	Low
Length	Link length (km)
freeflowSpeed	Free flow speed (km h^{-1}), value defined by Highways Agency
rawFlow	Flow for the link – number of vehicles over the 15 minute time period
flowDataType	Values indicate whether data is observed or infilled
flowDataNumberPoints	Number of records used for infilling, 0 indicates observed data is used
Incident	Flag indicating whether travel time for the link has been unusually high
Roadworks	Field not used at present – set to 0
adjFlow	Adjusted flow (average for count of vehicles (rawflow), time period and day ID) for use when calculating delays
totalDelay	'Best 3 source MADJ' estimate of total delay (seconds) calculated using the formula:

	$\text{totalDelay} = (\text{MADJ_avgJT} - (\text{length} / \text{freeflowspeed})) \times (\text{adjflow})$
recDelay	Recurrent portion of total delay – delay which is caused by congestion (determined by time of day and day of the week)
incDelay	Non-recurrent portion of total delay – delay caused by an incident other than usual congestion (e.g. accidents)
rwkDelay	Not used
Source	Source data has been obtained from

Due to the extensive amount of information available, a data reduction exercise was initially required. Firstly, a single year of data was selected for further investigation: 1 January 2008 to 31 December 2008 for the 146 links (i.e. junction to junction sections of road) along the route. A single year was selected to enable a preliminary analysis to be performed at the start of the project. Secondly, a series of time slices for each day were chosen for further investigation. The HATRIS data have a high temporal resolution with measurements of journey time and traffic flows taken every 15 minutes throughout each 24 hour period. Journey time is the measured variable across each of the links and from this the average speed across each link is calculated using:

$$\text{Average speed (km h}^{-1}\text{)} = \text{Link length} / \text{Journey time}$$

The speed data are then included in the database for each link and it is these data that will be extracted and used for the analysis. Four 15 minute time intervals were selected for daily analysis, at 0000h, 0800h, 1200h and 1800h, to allow for analysis of the morning and evening rush hours, plus a daytime and a night time timeslot. The four time slices relate to the 15 minute period from the given time, i.e. 0000h applies to the time period 0000h to 0014h; 0800h to the period 0800h to 0814h; 1200h to the period 1200h to 1214h; and 1800h to the period 1800h to 1814h.

For this study, the Merged All Data for Journeys (MADJ) speed was selected for particular investigation. The MADJ data (covering both journey time and speed) was chosen for its reliability as it is generated using a ‘best of three sources’ approach using Trafficmaster, MIDAS and ITIS data. The recorded value in the database is taken from the source which is considered to be the best available and is used to provide the MADJ journey time. For the motorway network, these data are usually obtained from the MIDAS (although where there are instances of missing data then the ITIS source will be used). Journey time was not selected as the variable to be used in the analysis as each link differs in length and so the average time taken to cross each link would not be directly comparable between links.

3.3.3 NIMROD Precipitation Radar

NIMROD precipitation radar data were obtained from the Met Office archives via the British Atmospheric Data Centre. Around the UK, there are a number of precipitation radars which collect data that are subsequently processed by the NIMROD system at the Met Office. At each site, radar scans are carried out at different elevations to give the best possible estimate of precipitation at the ground surface. NIMROD data have a spatial resolution of 1 km and are available at 5 minute intervals, and the units of measurement for precipitation rate are $\text{mm h}^{-1} \times 32$. To correspond with the HATRIS data, NIMROD data for the corresponding time are used to investigate the effects of precipitation both along the entire route and at more local scales where convective precipitation storms are likely to impact significantly on local traffic speeds.

3.3.4 GIS Analysis

GIS was used to overlay the HATRIS and NIMROD datasets to identify any initial relationships between precipitation events and traffic speed. The centre point of each of the 146 operational links (halfway between the start and end junctions) along the route corridor was calculated to provide a point where the precipitation rates from the NIMROD data could be extracted for each time slice. GIS maps were then created using the HATRIS and NIMROD data and precipitation values extracted for each of the motorway links (Figure 3.2).

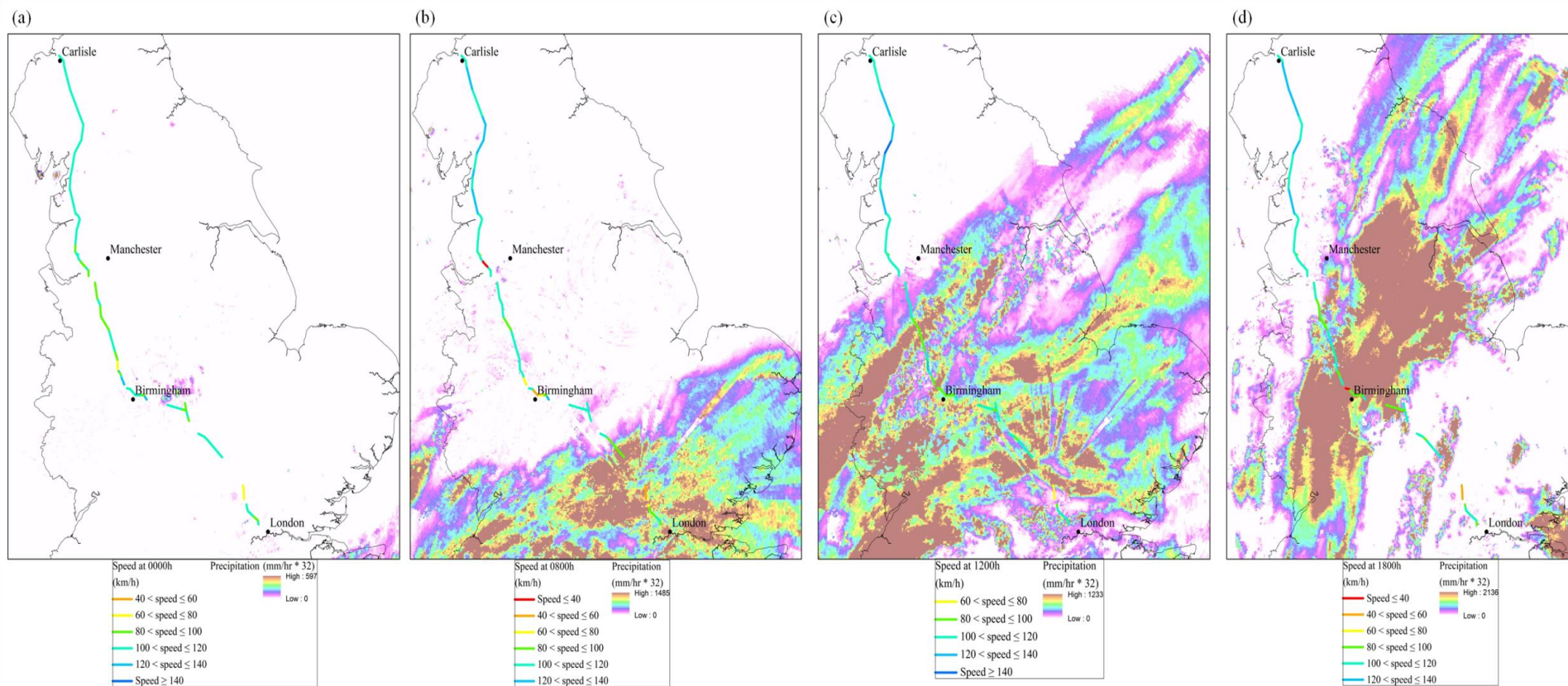


Figure 3.2 Maps for 11 January 2008 – (a) 0000h, (b) 0800h, (c) 1200h and (d) 1800h

3.4 Results and Discussion

3.4.1 Route Level Analysis

Linear regression was initially carried out on the data to identify the relationship between traffic speeds and instantaneous precipitation along the entire route. Although some of the fundamental statistical assumptions of linear regression have been violated (primarily the normality assumption, as the data is skewed), it is used purely as an exploratory tool and enables a feel of the data to be obtained. Although there is an identifiable but weak relationship on some days, as shown in Figure 3.3a, on others the relationship is almost absent (Figure 3.3b). However, in all cases a clear overall negative trend is present. Based on this preliminary analysis, it is reasonable to assume that a relationship exists, yet it is complex and not clearly defined. Other variables such as traffic volume, road capacity, antecedent rainfall and precipitation duration will also need to be taken into account in future research.

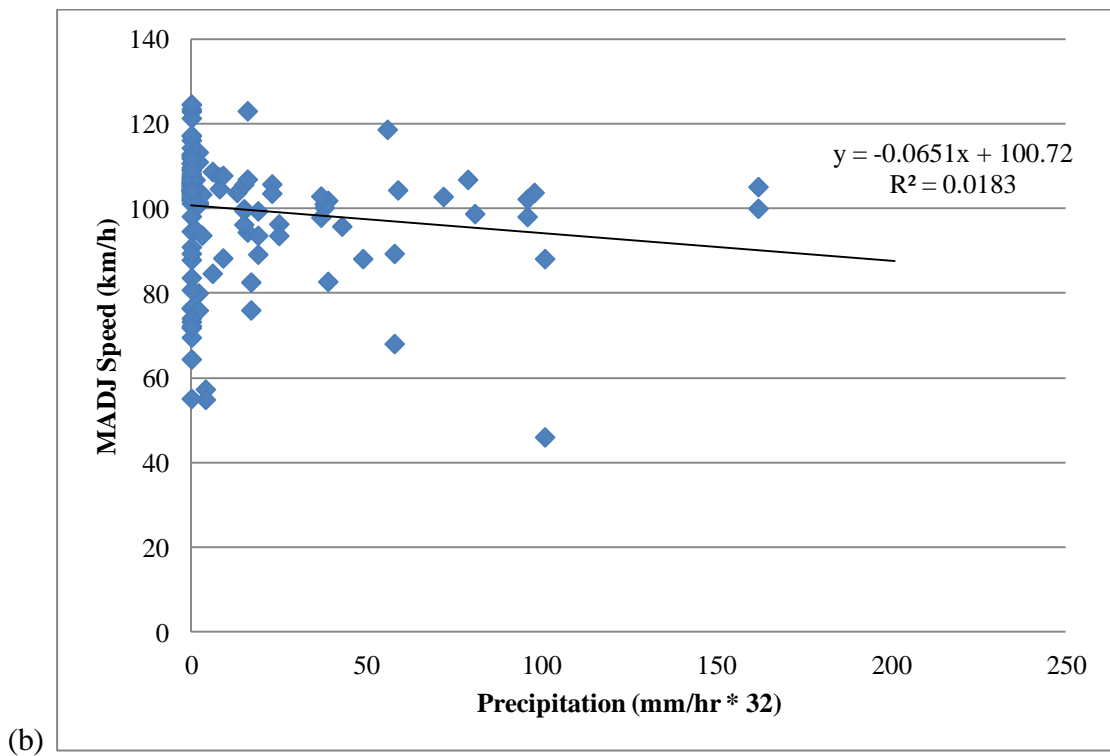
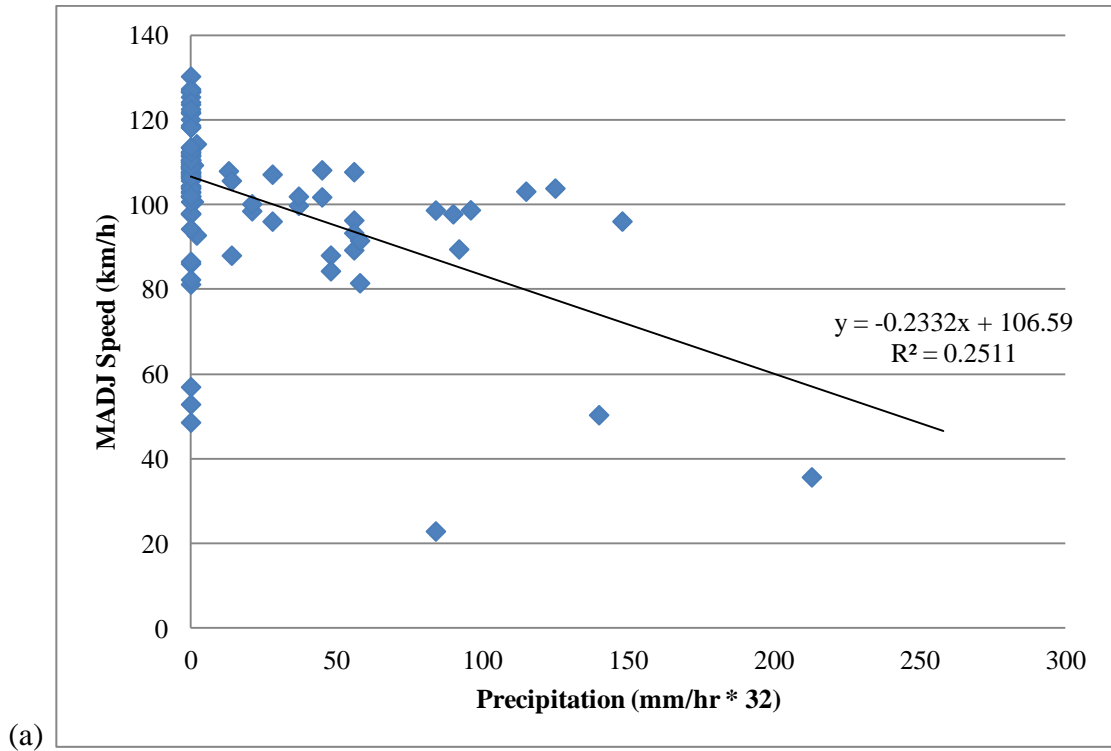


Figure 3.3 (a) Linear regression for the entire route, 11 January 2008, 1800h (b) Linear regression for the entire route, 3 June 2008, 1200h

To test the significance of the relationship between speed and precipitation, the Spearman correlation coefficient was calculated. As a non-parametric test, using the Spearman correlation coefficient allows for identification of both the strength and the significance of the relationship between the variables despite the data being skewed and not normally distributed. As shown in Table 3.3, the Spearman correlation coefficient corroborates the linear regression results (Figure 3.3) with a negative relationship between the variables in both instances, significant at the 99% level. The correlation coefficients between the two variables for both examples shown in Table 3.3 are not particularly high, again suggesting that there may be other factors influencing the relationship between the two variables. The Spearman correlation coefficient for both examples shown here is much stronger than the Pearson correlation, reinforcing that a non-parametric test is the most suitable to use for this particular data set.

Table 3.3 Spearman correlation coefficient results for speed and precipitation

	Spearman correlation coefficient	Significance
11 January 2008, 1800h	-0.514	99%
03 June 2008, 1200h	-0.340	99%

At the start of this investigation, it was hypothesised that there were potentially two thresholds of failure on the road network with respect to precipitation:

1. Low to moderate rain – sufficient enough to impact upon visibility and therefore slightly reducing vehicle speeds,
2. Heavy rain – inducing flooding on the carriageway and impacting significantly on vehicle speeds.

From the analysis, neither of these thresholds appears to exist in the dataset. However, there is a threshold evident at 0 mm h^{-1} , i.e. between precipitation / no precipitation, with the greatest speeds occurring when there is no precipitation and speeds decreasing when there is precipitation. Previous studies have identified that drivers on UK motorways are aware that there is a need to reduce their speed in wet weather conditions (Edwards, 1999b), although most only make a marginal reduction (Edwards, 2002). This awareness of the need to reduce speed may be one factor which contributes to the observed slower speeds during precipitation events over the course of the study period.

In order to test the existence of the no precipitation / precipitation threshold, Welch's *t*-test (assuming unequal variance) was used to determine if there is a significant difference between vehicle speeds with / without precipitation. The assumptions of Welch's *t*-test are:

1. The samples have unequal variances;
2. The populations have different standard deviations;
3. The populations are normally distributed.

The first two assumptions are satisfied by the speed data obtained from HATRIS. The third, that the data is normally distributed, is not met. However, Welch's *t*-test is still appropriate to use when data is not normally distributed if the sample sizes are large

enough and as the samples used here are large (between 654 and 1273 when there is no precipitation, and between 56 and 440 when there is precipitation), then it is appropriate to continue using Welch's *t*-test.

The results were variable, with some instances showing a significant difference at the $\geq 90\%$ significance level. However, there are also many instances where there is no significant difference between the two data sets. This further reinforces the conclusions drawn from the linear regression analysis that the relationship between precipitation and traffic speeds is complex and requires more investigation to be understood fully. Indeed, over the year of analysis there is little consistency or marked seasonal differences between months (Figure 3.4). The months with the highest percentage of analyses (all time slices) which are significant at the $\geq 90\%$ level are January (11.34% of analyses significant), May (11.11%) and November (10.78%). In contrast, the months with the lowest percentage of analyses which were significant at the same level were February (1.67%), August (6.6%) and September (6.45%). February 2008 was a dry month, with England receiving 63% of the average rainfall for the month, based on the 1971 – 2000 average (Met Office, 2008a, 2008b). December was another drier than average month in 2008 with England again having less than average rainfall at just 65% of the 1971 – 2000 average (Met Office, 2008c).

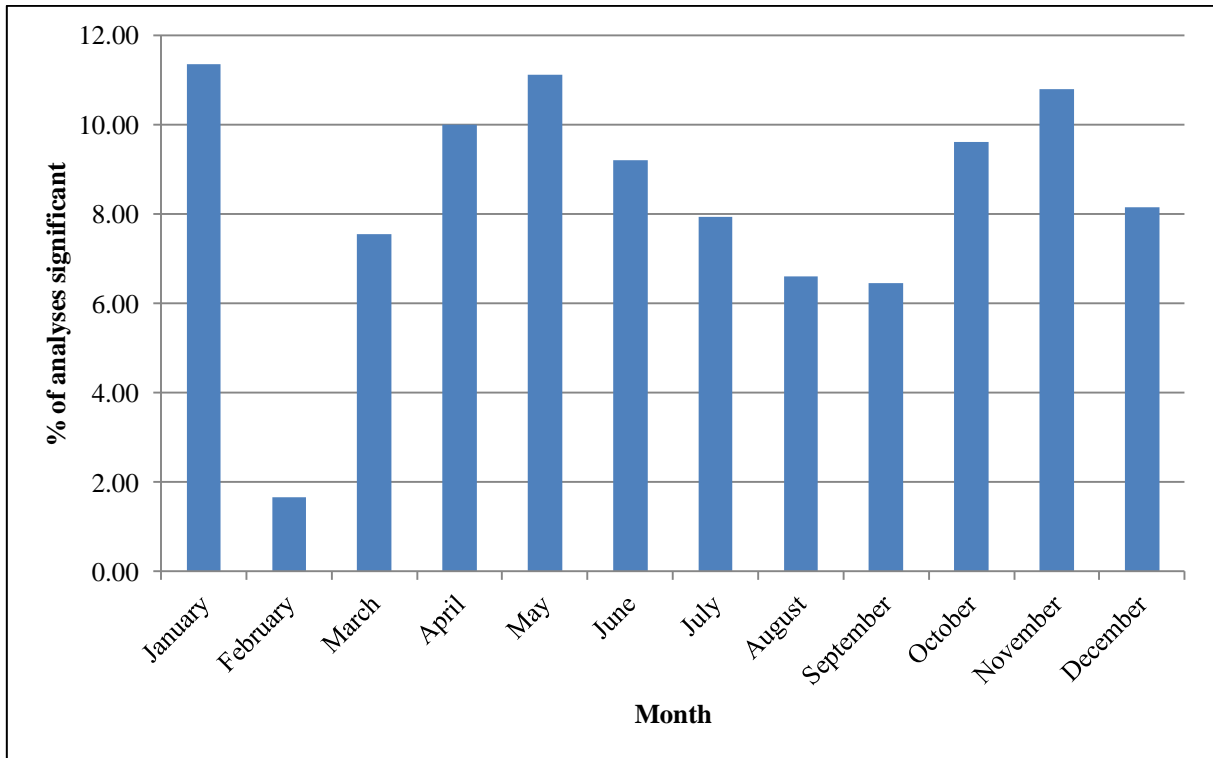


Figure 3.4 Percentage of Welch's *t*-test analyses significant at the 90% level, for all time slices (mean speed in wet weather is significantly lower than mean speed in dry weather)

Although in the majority of cases speeds are reduced when precipitation occurs, there are a number of instances which are an exception to the rule. In these cases, speed in wet weather is higher than the mean speed in dry weather although these analyses tend not to be significant. The magnitude by which the average speed in wet weather is greater than in dry weather varies considerably with some occasions where wet weather speeds are faster by as little as 0.1 km h^{-1} and others where the difference is far larger, as much as 20 km h^{-1} .

Having identified the existence of the no precipitation / precipitation threshold, the average speed reduction between dry and wet weather was calculated for all time slices during each month of 2008. The results vary greatly from month to month, as shown in Figure 3.5. The largest reduction in speed in wet weather occurs in November with speeds reduced by almost 4 km h^{-1} on average when precipitation occurs. Although the overall trend is that speeds decrease when precipitation occurs, there are two months (February and October) when the data suggests that an increase in speed occurs under wet weather conditions, i.e. speeds are slower in dry weather. These increases, although small, are unexpected and this reinforces the need for further analysis. February was a particularly dry month in 2008 and there are also some data missing (both from the HATRIS and NIMROD data sets) which may have affected the results in this month.

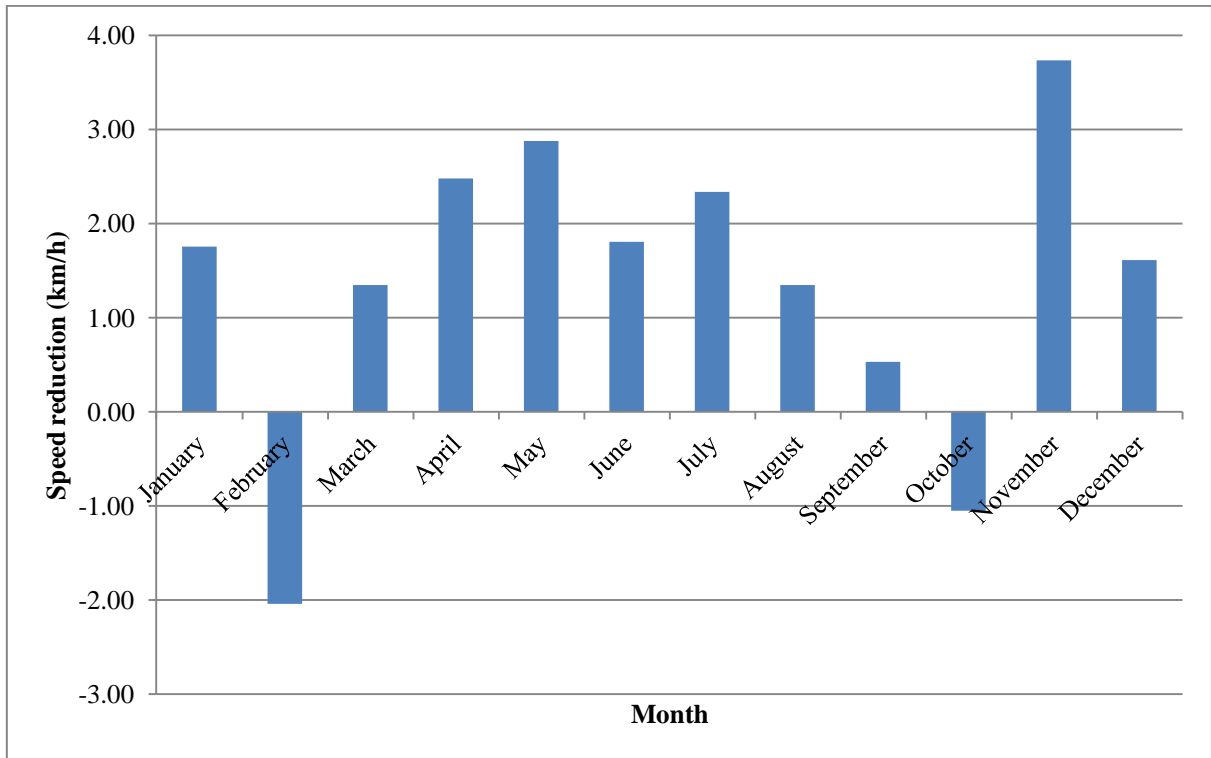


Figure 3.5 Average speed reduction during precipitation along the entire route for each month during 2008

The volume of traffic should be an additional significant contributory factor in this relationship. Therefore, to determine whether there is a stronger impact of precipitation on traffic speeds at a certain time of day, analyses at 0000h, 0800h, 1200h and 1800h were investigated to determine the percentage of instances where the mean speed differed significantly when there was precipitation compared to when there was no precipitation at these time intervals.

Figure 3.6 shows the results for each month and time slice indicating the percentage of analyses during each month where the difference in means was significant at the 90%

level or better. Taking January 2008 as an example, precipitation had a significant impact (at the 90% level or above) on 11.11% of journeys along the route at 0000h, 11.54% of journeys at 0800h, 4.00% of journeys at 1200h and 15.38% of journeys at 1800h. Similarly, the Welch's *t*-test results for June 2008 show that precipitation had a significant impact on 13.79% of journeys at 0000h, 3.70% of journeys at 0800h, and 10.34% of journeys at 1800h. No journeys at 1200h in June were significantly impacted by precipitation.

It was hypothesised that precipitation would have a greater impact on traffic speeds during the busiest times of use on the motorway, where the greatest traffic flows occur (i.e. 0800h and 1800h). However, from the analysis, there is no clear pattern to suggest that precipitation has a greater impact on traffic speeds at one time of day compared to others. Indeed, taking June as an example, precipitation has the greatest impact at 0000h with 13.79% of analyses showing that speeds when there was precipitation were significantly slower at the $\geq 90\%$ level (Figure 3.6).

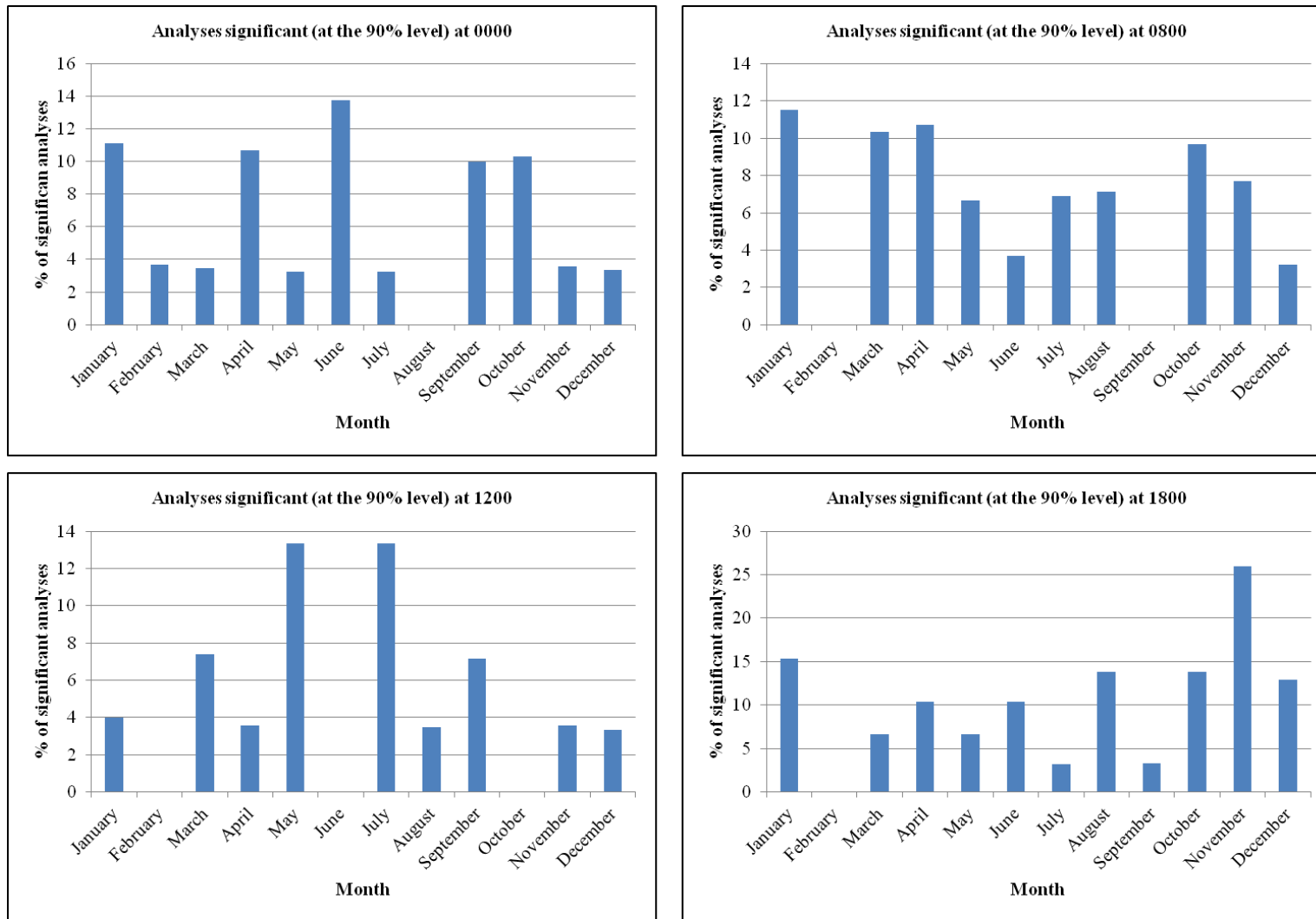


Figure 3.6 Welch's t -test analyses significant at or above the 90% level at (a) 0000h, (b) 0800h, (c) 1200h and (d) 1800h

Speeds tend to decrease along the route at all time slices when precipitation occurs and the average reduction ranges in magnitude from 0.18 km h⁻¹ (March, 0800h) to 10.53 km h⁻¹ (November, 1800h). As with the monthly analysis which incorporated all time slices, there are a number of instances where the average speed in wet weather is greater than the average speed in dry weather. This occurs during six months at 0000h, five months at 0800h, and during 3 months at 1200h and 1800h. It is possible that this occurs often at 0000h as there is much less traffic on the road than during the daytime and so there are fewer vehicles which are affected. Where there are fewer vehicles on the road, drivers may be able to maintain their speed and precipitation is likely to have less of an impact than at 0800h or 1800h for example when roads are at or near the physical capacity. However, the increase in speeds in wet weather observed at times of peak traffic is unexpected. As a result of these findings, it is clear that further investigation is needed incorporating traffic flows to develop understanding of this complex relationship between precipitation and traffic speeds further.

3.4.2 Link Level Analysis

Analysis at the route level highlighted the need for further analysis at a local level. Welch's *t*-test was performed on each individual link along the route, comparing speeds when there is no precipitation to those when precipitation does occur. The analysis for each link incorporates all time slices studied to gain an overall insight into the impact of precipitation on the links. The results vary along the route with 38% of links exhibiting a significant reduction in the average speed in wet weather (at the 95% level). On the majority of the remaining links whilst there is a reduction in average speed, it is not

significant. On a very small number of links, there is a slight increase in average speed in wet weather (M1 junction 10 to 11 and M6 junction 4 to 4A). Link speed reductions along the northbound route are shown in Figure 3.7. Although speed reductions are observed on most of the links, the magnitude of the reduction is often fairly small – on the northbound carriageway, only 12% of links have a speed reduction greater than 4%. The links where precipitation causes the greatest reductions in speed are between junctions 8 and 10 of M6, through Birmingham.

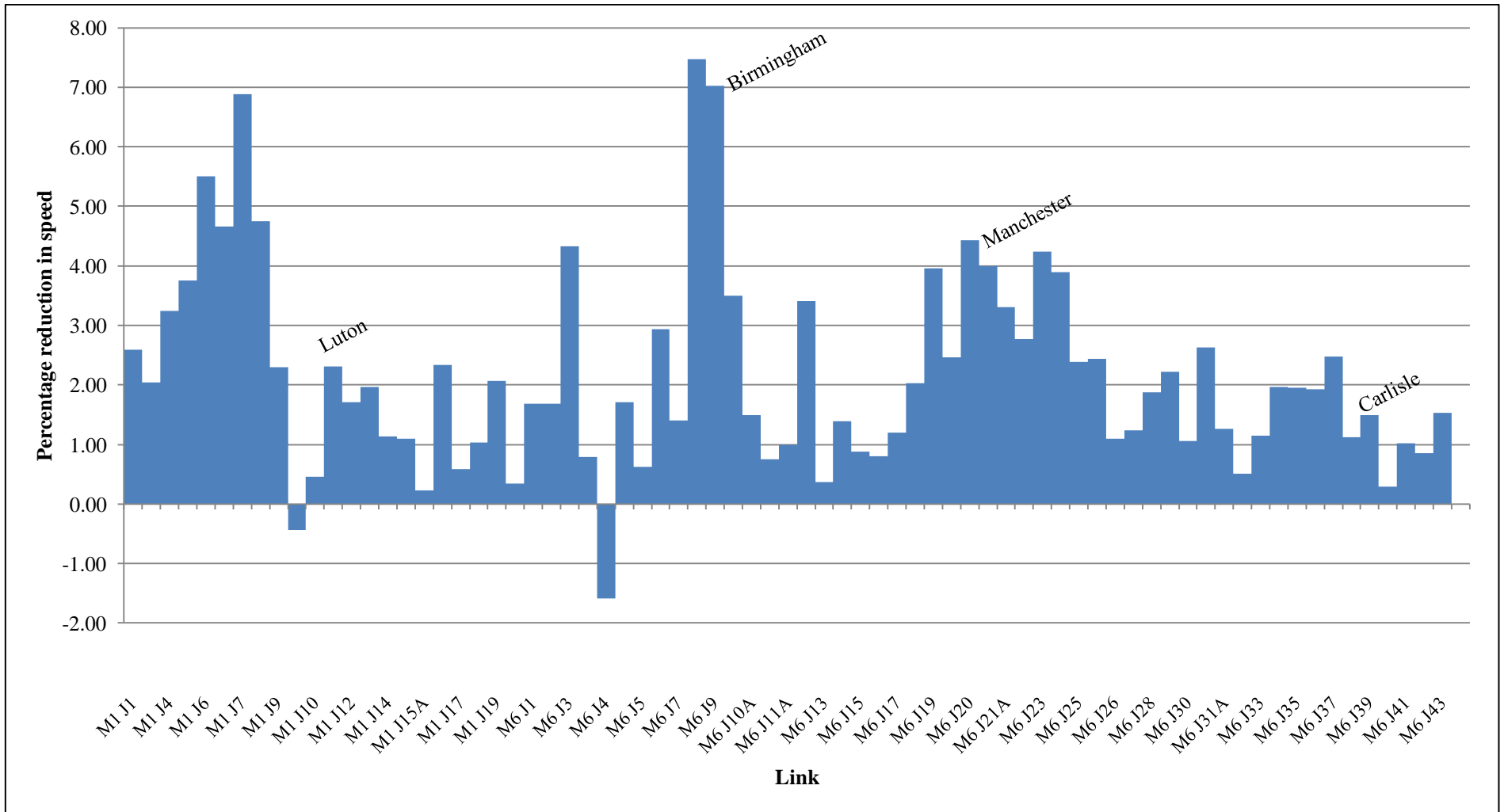


Figure 3.7 Average speed reductions due to precipitation on the northbound carriageway (London to Carlisle)

It is evident from examining speed reductions along the entire route that the greatest reductions in wet weather occur in urban areas. In Figure 3.7, there are clearly defined peaks on links near to major cities, in particular Birmingham and Manchester. The likely explanation for this is that these links have much higher volumes of traffic and when precipitation occurs, the speed reduction is larger as a direct result of the greater number of vehicles on the link. The variation in speed reductions may be as a result of the differing flows on the links – for example links with smaller speed reductions may be those where flows are lower and those with greater speed reductions are likely to be links with greater flows operating at or near the physical capacity of the road.

The influx of vehicles from neighbouring motorways may also contribute to greater speed reductions on some links – where another motorway joins the M1 or M6, then traffic flows are much higher and a greater number of vehicles are impacted by precipitation leading to a greater reduction in speed during wet weather events. Junction 6A of the M1 is the M25 interchange and the M1 gains a high volume of additional traffic at this point which may explain why the speed reduction is much higher on this link than on those surrounding it. Junction 7 of the M1 has a particularly high speed reduction in wet weather and this is likely to be as a direct result of the increase in traffic volume at this location. Junction 8 of the M6 where the motorway meets the M5 is another key interchange and again, a large reduction in traffic speeds is observed at this link. Likewise where the M6 Toll rejoins the M6 (at junction 11A), traffic volumes increase greatly and as a result, the impact of precipitation is exacerbated at this location and along the next few links.

Widening of the carriageway helps to increase the physical capacity of the motorway and may in turn reduce the impact that precipitation has on these links. One such example is junctions 29 to 32 of the M6. The reductions in speed during precipitation are much less on the links between these junctions than on the links either side and this may be a direct result of the increased capacity added by the fourth lane, reducing delays during precipitation. The variation in speed reductions along the route and the individual nature of the relationship between speed and precipitation on each link highlights the need for further in depth research at the link scale to identify what the relationship is between speed and flow on each link and to determine how it is affected by precipitation.

3.5 Summary

The analysis detailed in this chapter was carried out initially to determine the impact of precipitation on traffic speeds at the route level, with a view to determining existing thresholds. It is clear that there is no single factor relationship between precipitation rate and speeds across the motorway links. However, there is a threshold which often exists between speeds when there is no precipitation and when there is precipitation – the greatest speeds occur when there is no precipitation and speeds immediately decrease when there is precipitation. The relationship between precipitation and traffic speeds is shown to be a complex, non-linear and temporally variable one which requires further investigation. From the results obtained in this study, it is clear that no universal relationship exists that can be applied at a national level. Further analysis at the local level examining the difference in speeds when there is no precipitation and when

precipitation occurs (using a Welch's *t*-test) indicates that whilst there is a reduction in speed in wet weather on much of the route, the magnitude of reduction varies greatly. The most vulnerable links tend to be in urban areas with average speeds being reduced by up to 7%. Detailed data from analysis at a local scale is then sufficient as a starting point for a national climate change impact assessment of the impact of precipitation on the road network, but other traffic parameters must now be investigated, particularly traffic flow, to further develop understanding of how precipitation impacts on the UK motorway network.

Chapter 4 - The Impact of Precipitation on Speed – Flow Relationships along a UK Motorway Corridor

4.1 Introduction

Whilst the impacts of weather conditions on the individual traffic parameters of speed and flow have previously been studied (Edwards, 1999a; Martin *et al.*, 2000; Smith *et al.*, 2004), there is little work looking at how weather affects the actual relationships between traffic variables. This chapter begins to address this research gap, investigating how precipitation affects speed – flow relationships along a major transport corridor which is of great economic importance to the UK. Speed (km h^{-1}) and flow (number of vehicles per 15 minutes) data collected from state of the art traffic monitoring technologies are utilised to investigate for the first time location specific impacts of precipitation on the UK road network.

4.2 Impact on Traffic Parameters – Speed and Flow

Previous studies examining how precipitation affects the traffic parameters of speed and flow are summarised in Table 4.1. The majority focus on the variable of speed, with the overall trend that there is a reduction in speed and flow as precipitation increases. However, as Chapter 3 has shown the reduction in speed is often the same regardless of precipitation amount or intensity (Agarwal *et al.*, 2005).

The majority of work investigating how speed or flow are affected by weather has been undertaken in the US and Canada (Agarwal *et al.*, 2005; Kyte *et al.*, 2006; Smith *et al.*, 2004; Stern *et al.*, 2004). Whilst research in countries outside of the US has been undertaken (e.g. Cools *et al.*, 2010; El Faouzi *et al.*, 2010), there are far fewer UK studies which closely investigate how speed and flow are affected by precipitation (Al-Hassan & Barker, 1999; Edwards, 1999a; Edwards, 2002; Hooper *et al.*, 2012). Research into the impacts of precipitation across the UK is far less recent with most studies now being at least ten years old and so it is timely to use new data sets to further establish more recent impacts of precipitation on speed and flow across the country.

Table 4.1 Summary of previous studies investigating the impacts of precipitation on road traffic parameters

Authors	Location	Variable	Impact
Agarwal <i>et al.</i> (2005)	Twin Cities, US	Capacity Speed	More than 0.25 inches of rain: Capacity reduction of 10 – 17% Speed reduction of 4 – 7%
Al-Hassan & Barker (1999)	Edinburgh, Scotland	Traffic activity	Significant reduction in traffic activity during rainfall events: 4% at the weekend; less than 3% during the week
Andrey <i>et al.</i> (2013)	Canada	Speed	Results do not provide strong evidence that drivers become acclimatised to local weather patterns
Cools <i>et al.</i> (2010)	Belgium	Traffic intensity	Rainfall diminishes traffic intensity The impact of weather is different at each location studied
Edwards (1999a)	Wales	Speed	Traffic speed slightly (and significantly) reduced when precipitation occurs Highlights the need for studies over a greater area
Edwards (2002)	Wales	Speed	Whilst a reduction in speed occurs during wet weather, the reduction does not compensate for the increased hazards during inclement weather
El Faouzi <i>et al.</i> (2010)	Europe	Speed Flow	During precipitation speed, acceleration, traffic flow and capacity all decrease Speed variation and congestion severity increase
Hooper <i>et al.</i> (2012)	England	Speed	No clear relationship between speed and precipitation amount Key threshold of 0 mm h ⁻¹ identified – fastest speeds occur when there is no precipitation and speeds immediately decrease when precipitation occurs
Hranac <i>et al.</i> (2006)	Baltimore, Seattle, Minneapolis, St. Paul, US	Speed	Reductions increase with intensity Light rain: Free flow speed reduced by 3% Speed at capacity reduced by 9% Maximum reductions: Free flow speed 6 – 9% Speed at capacity 8 – 14%
Ibrahim & Hall (1994)	Mississauga, Canada	Speed	Reduction in free flow speed of 5 – 10 km h ⁻¹
Lamm <i>et al.</i> (1990)	New York, US	Speed	No effect of wet road surface on traffic speed
Martin <i>et al.</i> (2000)	Utah, US	Speed	10% speed reduction in wet weather
Maze <i>et al.</i> (2006)	Minneapolis, St. Paul, US	Speed	Up to 10% reduction in wet weather
Smith <i>et al.</i> (2004)	Virginia, US	Speed Flow	Light rain decreases capacity by 4 – 10% Heavy rain decreases capacity by 25 – 30% The presence of rain decreases speed by 5 – 6.5%
Stern <i>et al.</i> (2004)	Washington, US	Travel time	11% increase in travel time at peak periods during a precipitation event 13% increase in travel time at off peak periods
Tsapakis <i>et al.</i> (2012)	London, UK	Travel time	Travel times increase when rain occurs Weather effects vary considerably depending on a number of factors
Unrau & Andrey (2006)	Canada	Flow	Rain had a small impact at low flows and a larger impact at high flows

A negative relationship between precipitation and the traffic parameters of speed and flow is often observed, i.e. as precipitation increases, speed and flow decrease (Agarwal *et al.*, 2005; Cools *et al.*, 2007; Hranac *et al.*, 2006; Smith *et al.*, 2004). The magnitude of the impact of precipitation varies between locations, highlighting the importance of understanding how road networks are affected at a local scale. Reductions in speed vary from just 3% to 14%. There is a far greater range in the magnitude of flow reduction with the greatest impacts observed when traffic flows are high (Unrau & Andrey, 2006). Reductions in flow can be as little 4% and as great as 30%. Smith *et al.* (2004) investigated the impacts of precipitation on highway traffic flows in Virginia, US and discovered that both capacity and speed on the highway were affected during a precipitation event, with the possibility of a 5% to 6.5% speed reduction. It is also likely that journey times and delays would increase significantly and traffic congestion would increase along the affected section of road. A similar study by Hranac *et al.* (2006), also on US roads, identified that free flow speed, capacity and speeds at capacity are all affected during precipitation events of varying intensities.

Whilst the majority of studies use data from the United States, the reduction in speed and flow has also been observed in the UK. Traffic volumes in Scotland were reduced on days when precipitation occurred, with a reduction of up to 4% (Al-Hassan & Barker, 1999). Similarly, Edwards (1999a) observed a small but significant reduction in traffic speeds during a rainfall event on the M4 motorway in Wales. UK studies tend to consider a small area of the road network and as a result there is a need to research further how precipitation impacts across a greater area of the road network, both at a national and local scale.

4.3 Speed – Flow Relationships and the Speed – Flow Diagram

Investigations into relationships between the traffic parameters of speed, flow and density began with the work of Greenshields (1935), culminating in the fundamental traffic diagram (Figure 4.1a). The fundamental traffic diagram conveys the parameters of flow (vehicles per hour) and density (vehicles per km) and from these, speed can be inferred using the equation:

$$\text{flow} = \text{speed} \times \text{density}$$

The diagram allows the relationship between the three variables to be explored and defines critical thresholds for congested and free flowing traffic.

Since the initial development of the fundamental traffic diagram, many studies have revisited this work seeking to improve the models of relationships between the traffic parameters of speed, flow and density. Greenberg (1959) followed the work of Greenshields with research based on highways in Connecticut highlighting the increasing need to understand traffic dynamics as the number of vehicles using the road network increased and exceeded road capacities. A single regime model developed by Underwood (1961) built on the work of both Greenshields and Greenberg and assumed an exponential function between speed and density (Thankappan *et al.*, 2010). From investigating speed and flow, Drew (1965) concluded that there are three parameters which control congestion – optimum speed, optimum density and possible capacity. Later, Drake *et al.* (1967) identified that in all previous traffic flow modelling work, the speed – flow curve was categorised by a bell shaped curve (Quek *et al.*, 2009) and

evaluated the ability of the relationships between the traffic variables to predict flow values. The form of the speed – flow diagram commonly used in traffic management is shown in Figure 4.1b.

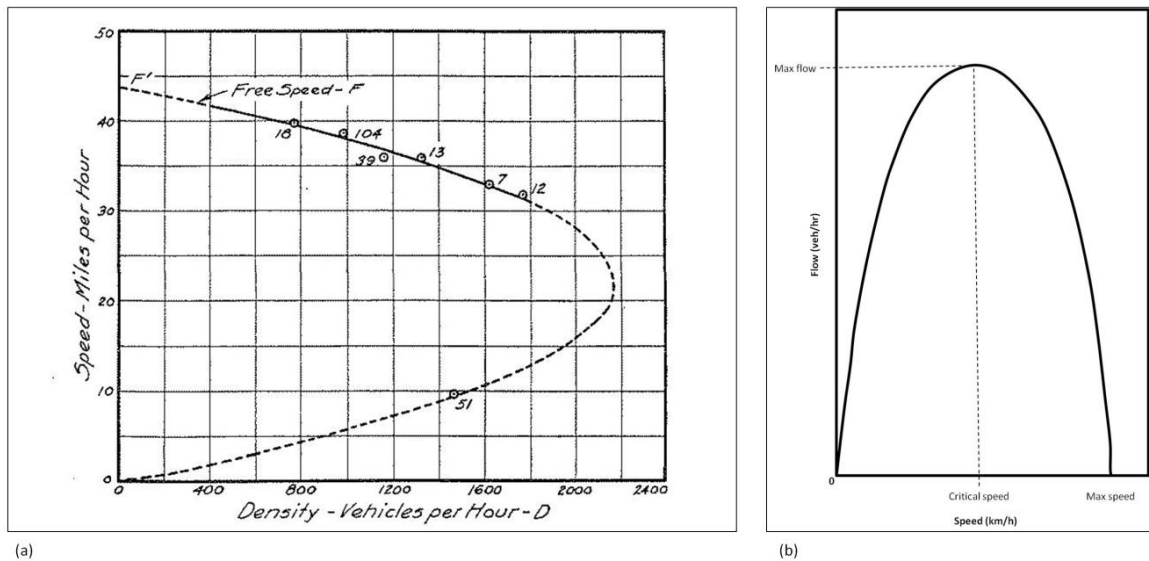


Figure 4.1 (a) Greenshields' fundamental traffic diagram (1935); (b) Speed - flow diagram used in traffic management (based on Gordon & Tighe, 2005)

Although the speed – flow diagram was created based on data from the United States, it can be assumed that UK traffic follows a similar pattern, although there is actually little research looking specifically at the relationship between the two variables in the UK. Existing studies (e.g. Smith *et al.*, 1996; Taylor *et al.*, 2008) have attempted to do so at a very general scale. These studies provide a good starting point for the investigation of speed – flow relationships in the UK but there is more research which still needs to be done.

Whilst the speed - flow diagram is useful in indicating the overall relationship between the two variables for a stretch of road, existing relationships do not consider the impacts of inclement weather on the relationship (Mahmassani *et al.*, 2009). Indeed, any relationships observed between speed and flow are based on the assumption of good weather, good visibility and dry surfaces (Kyte *et al.*, 2006). As Table 4.1 shows, few studies exist which have investigated how adverse weather, particularly precipitation, may impact on speed – flow relationships and those that do are small scale and largely based in North America. For example, Ibrahim & Hall (1994) examined the impacts of adverse weather on speed – flow relationships in Mississauga, Canada and concluded that under adverse weather, a downward shift in the speed – flow function was observed with adverse weather reducing the maximum observed traffic flows. Similarly, a study in Virginia found that when rain occurred, there was a free flow speed reduction of between 2% and 3.6%; a vehicle capacity reduction of between 10% and 11%; and a speed at capacity reduction of between 8% and 10% (Rakha *et al.*, 2007). It also identified that reductions in free flow speed and speed at capacity increased as rainfall intensity increased. The analysis in this chapter goes significantly beyond the scope of previous investigations by investigating local impacts of precipitation on speed – flow relationships at a local junction to junction scale.

4.4 Method

This chapter also uses the M1 – M6 motorway corridor from London to Carlisle (Figure 3.1). Speed and flow data are available for 138 links on the route via the state of the art HATRIS technology. This study is undertaken on a macroscopic scale, investigating the

properties of the traffic stream as a whole along individual road sections as opposed to a microscopic scale where the behaviour of individual vehicles would be investigated. It is common practice for a single speed – flow curve to be calibrated for a location across the year and hence, in this study, the 12 month period from 1 January 2008 to 31 December 2008 was used. To incorporate a range of speed and flow values into the analysis, four 15 minute time slices throughout the day were analysed – 0000h, 0800h, 1200h and 1800h. This includes the morning and evening rush hours when higher traffic flows would be expected. The purpose of this chapter is to investigate the overall speed – flow relationship on the motorway network and as a result all data for the entire year is included in the analysis. Data were not filtered by day of week as the intention was to create an overall picture of the relationship between the variables. The relationship between all weather speed and flow was investigated by polynomial regression with flow as the independent variable. The curves obtained from the analysis are then compared to the curve of the speed – flow diagram (i.e. Figure 4.1).

Once the initial speed – flow relationships had been investigated, the data were filtered to permit analysis for instances with / without precipitation. The presence of precipitation was again determined using Met Office NIMROD precipitation radar data. Data were also separated into congested and uncongested categories due to the differing characteristics of the traffic stream when it is either free flowing or congested, using the variable of speed to identify when traffic becomes congested. Using these categories allows for modelling of the traffic stream under each of these conditions and identification of the impact of rainfall based on the nature of the traffic regime (Unrau

& Andrey, 2006). Polynomial regression was then once again performed on these data sets to ascertain the impact of precipitation on the speed – flow relationship.

The speed at which traffic becomes congested was identified on inspection of the speed – flow diagrams created. The speed used was identified at the point of inflexion on the curve fitted to the data and in the majority of cases this speed was around 80 km h⁻¹ and so this is the value used to separate the data into free flow and congested categories. To determine whether traffic speeds were affected by precipitation, the 85th percentile of speed was used for each data set (no precipitation / precipitation). The 85th percentile represents the speed at which most drivers will drive at and is characteristic of reasonable driver behaviour (Donnell *et al.*, 2009) and is considered as the “...speed at or below which 85 percent of people drive at any given location under good weather and visibility conditions that may be considered as the maximum safe speed for that location” (page 3.4, Texas Department of Transportation, 2012). Therefore it is the value of speed most commonly used in traffic studies worldwide (Aljanahi *et al.*, 1999; Abbas *et al.*, 2011; Cottrell *et al.*, 2006).

4.5 Results and Discussion

The all weather analysis shows that a number of links on the route exhibit a relationship between speed and flow similar to that shown in the speed – flow diagram (e.g. Figure 4.2). However, this is not the case on all links. Despite the results being statistically significant at the 99% level or above on 88% of the links studied, the regression

analysis yielded a wide range of R^2 values. There are no R^2 values above 0.5 and 67% of the links have an R^2 value of less than 0.1. These low values of R^2 show that speed on the links is partially explained by flow but not entirely; there are clearly other factors which also impact on speed. This suggests that there are very different speed – flow relationships on the links, not all of which can be approximated by a quadratic curve as indicated by the speed – flow diagram. For example, Figure 4.3 shows one such link where there is no distinctive relationship between the two variables. Inspection of the location of such links indicates no common geographical factors as to why this would be the case, although there are other causes such as lane closures due to road works which would have an impact over a prolonged period of time. Unfortunately, HATRIS does not allow for identification of such issues and so care must be taken when considering why the results do not match the expected outcome.

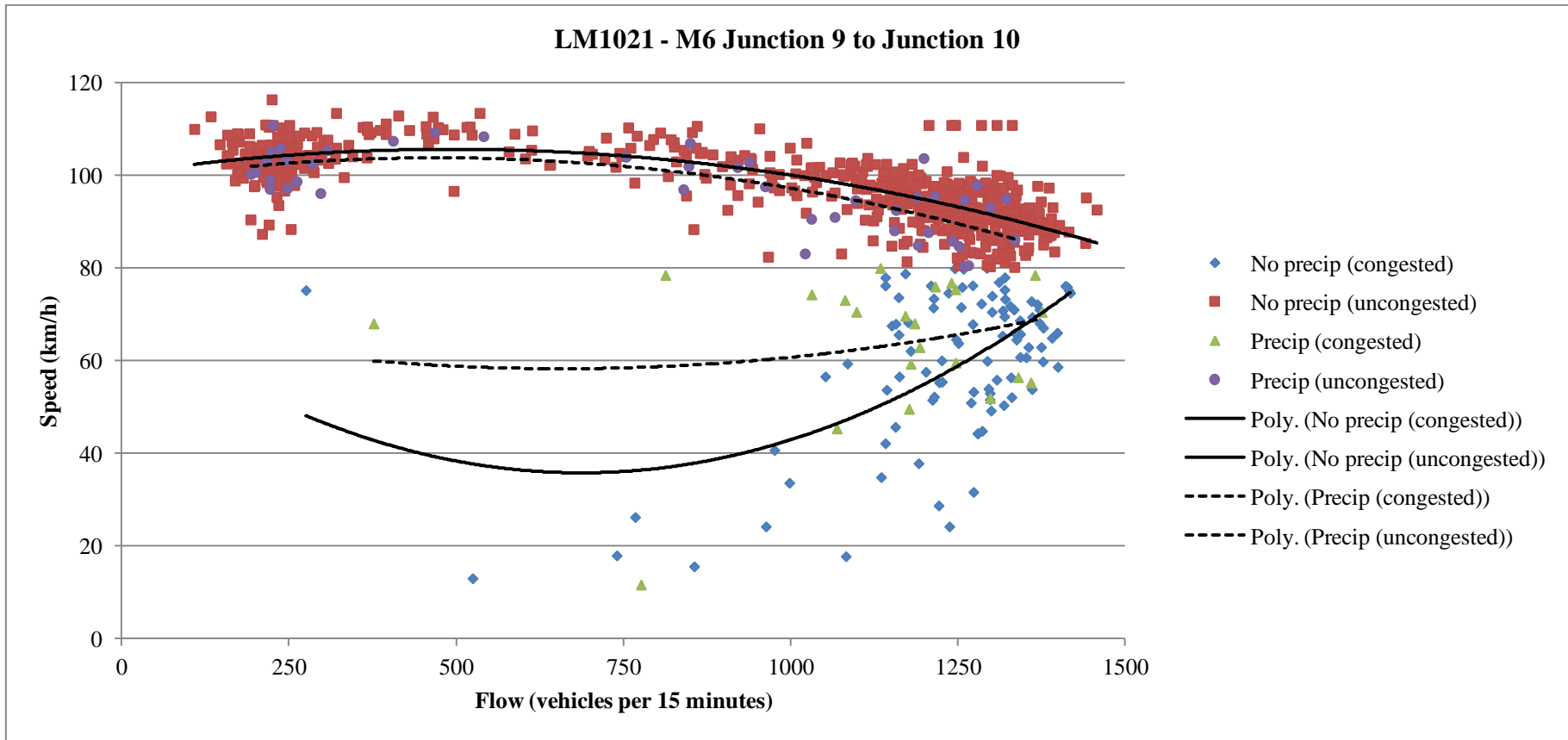


Figure 4.2 Polynomial regression for link LM1021 - M6 J9 to J10

(No precipitation, congested – $y = 0.00007x^2 - 0.1x + 70.149$; No precipitation, uncongested – $y = -0.00002x^2 + 0.0214x + 100.29$;

Precipitation, congested – $y = 0.00002x^2 - 0.0276x + 67.321$; Precipitation, uncongested – $y = -0.00002x^2 + 0.0221x + 98.515$)

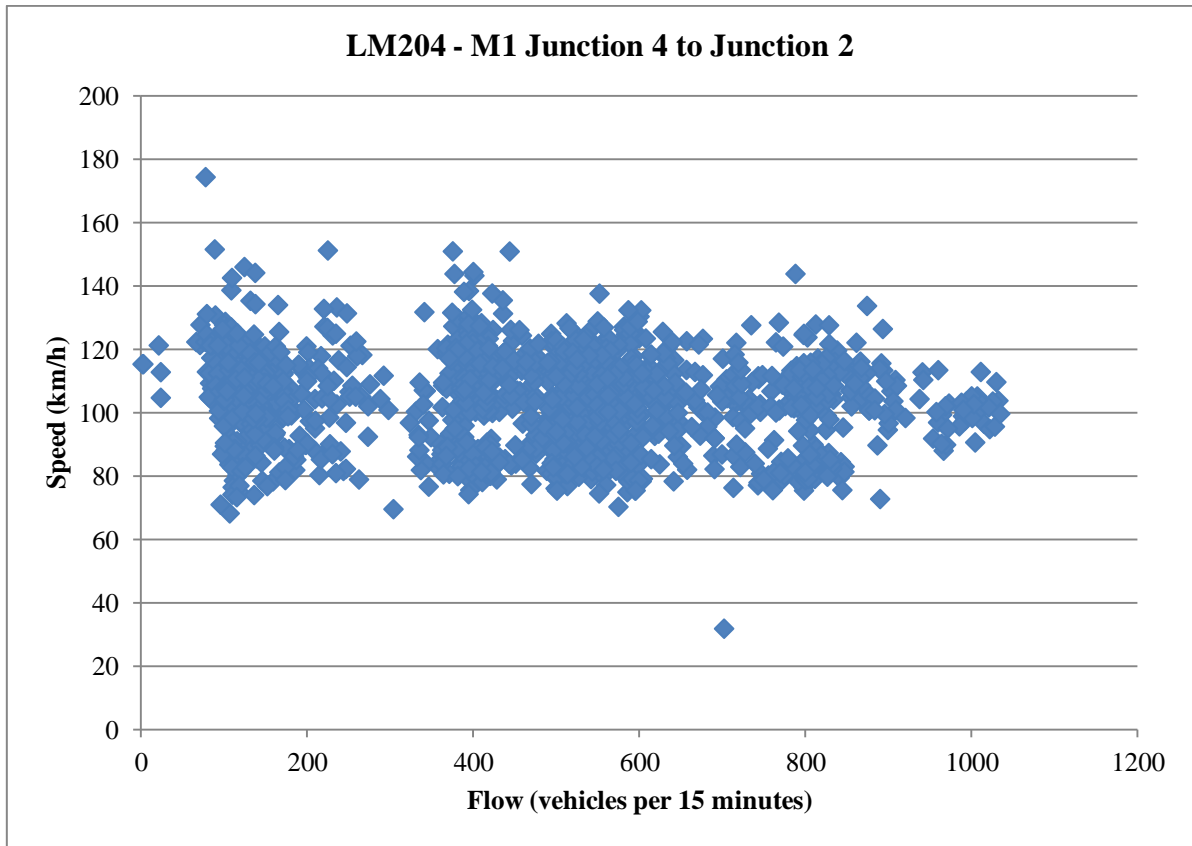


Figure 4.3 Data for link LM204 – M1 Junction 4 to Junction 2 (there is no junction 3 on the M1)

The speed – flow diagram, although based on observations, is a theoretical concept of the relationship between the two variables. In reality, the relationship may be different to the theoretical concept, especially at a local scale. As a result, polynomial regression may not be the most appropriate regression method to use on all the links studied, particularly when analysing the congested data. Where this seemed to be the case, a comparison was made between using polynomial regression for both uncongested and congested conditions, and using polynomial regression for the uncongested conditions and linear regression for the congested conditions. However, the use of linear regression

does not appear to improve the model and so the decision was made to continue to use polynomial regression for both congested and uncongested conditions where the link speed – flow relationship bears resemblance to the speed – flow diagram. Further research is needed in this area to identify fully the characteristics and improve modelling of speed – flow relationships on the UK motorway network at a local scale.

With respect to the precipitation / no precipitation analysis, a difference between the regression results is observed on the links where the speed – flow diagram holds. In each case, the precipitation curve is consistently below the no precipitation curve, indicating that speed and flow are reduced in wet weather conditions compared to in dry conditions (Figure 4.4). Although R^2 values are still low in both sets of analyses, a stronger relationship is apparent during precipitation. In dry weather, R^2 values are greater than 0.1 on 33% of the links, yet when there is precipitation R^2 values are greater than 0.1 on 46% of the links. The increase in the number of links with a greater R^2 value in wet weather may be a result of driver behaviour – during wet weather, drivers tend to reduce their speed, although the reduction may be marginal (Edwards, 2002), leading to more homogeneous driver behaviour than in dry weather where there may be a far greater divergence in speeds with some driving at excessive speeds. It appears that when speeds during precipitation are compared to speeds when there is no precipitation, there is a decrease in maximum speed but a slight increase in the lowest speeds. This may be a result of drivers adjusting their driving to compensate for the impacts of precipitation – it has been observed that drivers reduce their speed in wet weather (Edwards, 1999a; Edwards, 2002) and may also increase the distance between them and other vehicles. In doing so, the sudden need to brake is limited and may result

in a smoothing of congestion and therefore a slight increase in low speeds when precipitation occurs.

Table 4.2 shows the significance of the regression results for each category of analyses undertaken. The decrease in the number of links on which the regression analysis is significant when comparing the wet weather to dry weather may be as a result of a much greater spread of data in wet weather. Drivers tend to reduce their speeds in wet weather yet the reduction made is individual to each driver and their assessment of the weather and its impacts. As a result, the range of the data is likely to be much greater than in dry weather when most drivers will travel at or close to the speed limit of the road, unless there are other hazards present.

Table 4.2 The number of polynomial regression results that are significant for overall, no rain and rain polynomial regression analyses

	Overall	No rain	Rain
Significance \geq 99%	122	119	84
95% \leq significance $<$ 99%	5	5	18
90% \leq significance $<$ 95%	1	3	7
Significance $<$ 90%	10	11	29

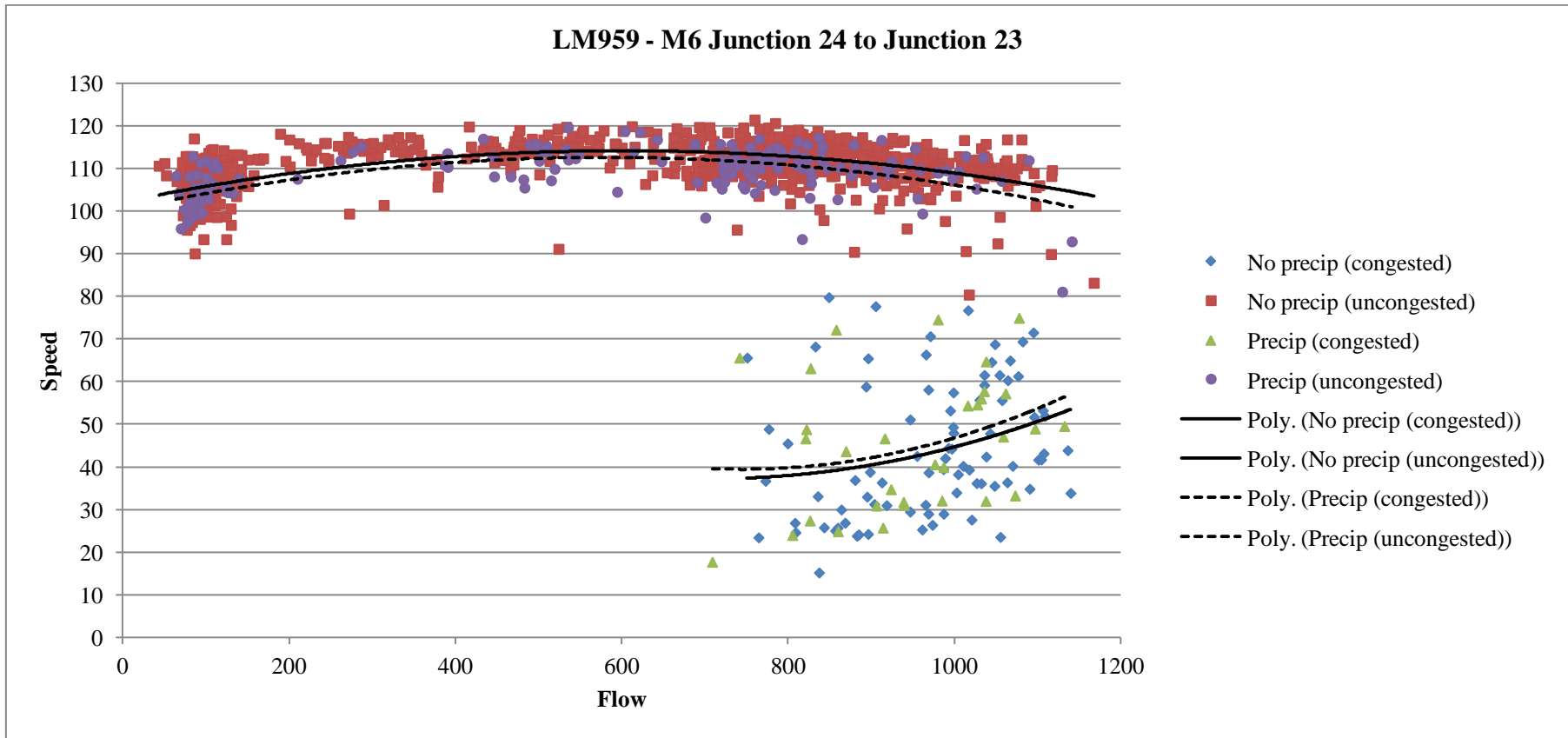


Figure 4.4 Polynomial regression for link LM959 - M6 J24 to J23

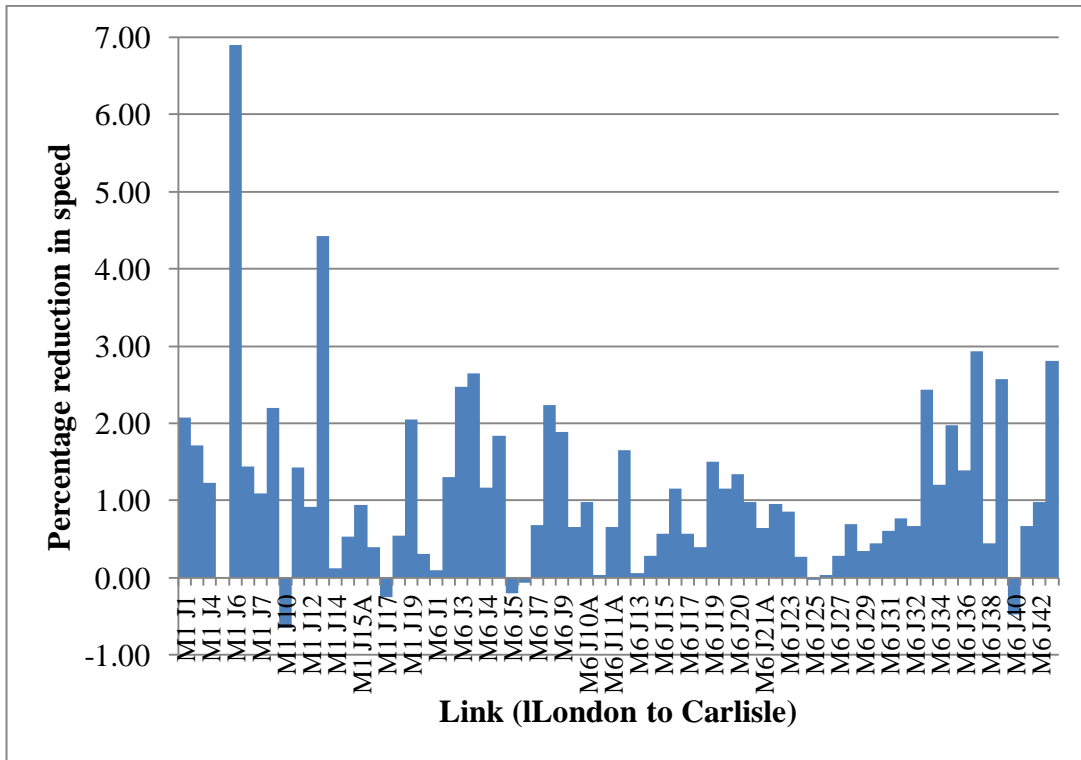
(No precipitation, congested – $y = 0.00009x^2 - 0.123x + 80.728$; No precipitation, uncongested – $y = -0.00003x^2 + 0.0399x + 102.14$;

Precipitation, congested – $y = 0.0001x^2 - 0.169x + 102.4$; Precipitation, uncongested – $y = -0.00004x^2 + 0.0427x + 100.23$)

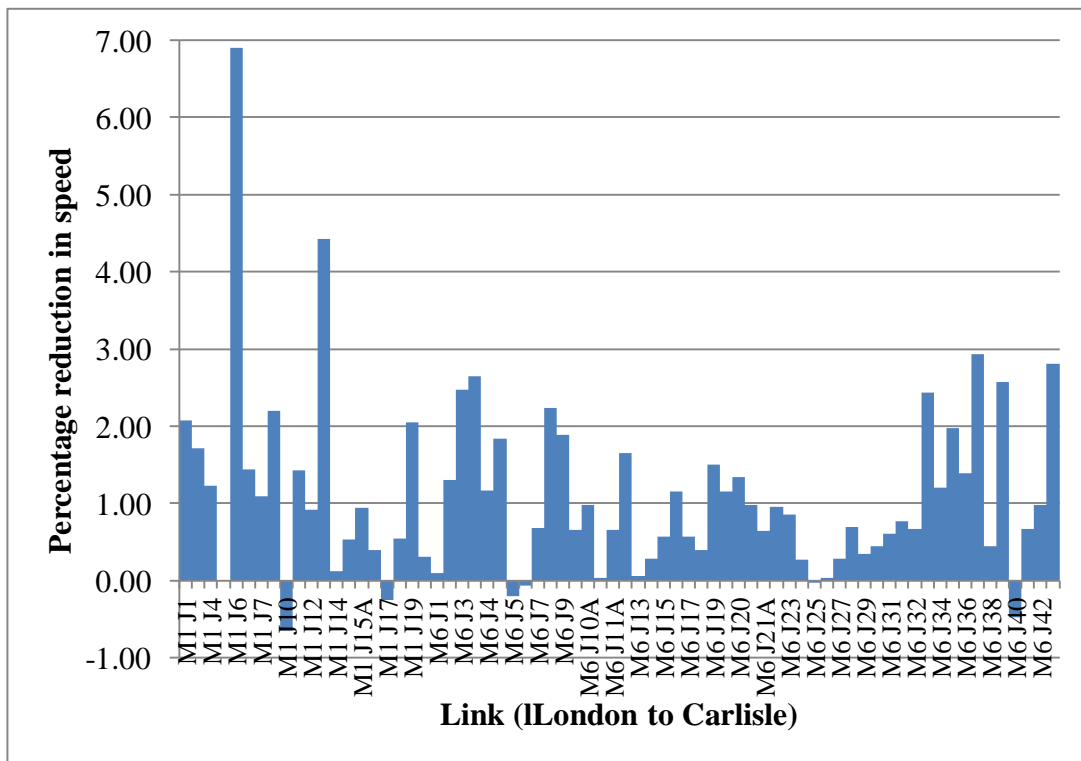
The findings of this study concur with those of Rakha *et al.* (2007), where a reduction in speed, maximum flow and free flow speed were observed in wet weather conditions. These results are also in broad agreement with other previous research investigating how precipitation impacts on traffic flow (Akin *et al.*, 2011; Hooper *et al.*, 2012; Mahmassani *et al.*, 2009; Smith *et al.*, 2004). A reduction in speed (at the 85th percentile) is observed on 93% of the links (129 links) indicating that precipitation does indeed adversely affect traffic speeds along the route. The magnitudes of reduction vary as shown in Figure 4.5 – some links exhibit only a minimal reduction and the greatest reduction on any one link is 6.9% (LM249 – M1 J6 to J6A). This concurs with the finding of earlier studies that whilst speeds tend to be reduced during wet weather, the reduction is often minimal (Edwards, 2002). Where an increase in speed is observed in wet weather, the increase tends to be minimal and often less than 1%, and as such it can be concluded that the difference between speeds in dry and wet weather on these links is almost nonexistent.

However, the reduction in speed and maximum flow in wet weather conditions is not observed on all links. Indeed, 58 links have a greater peak flow in wet weather than in dry weather, and two links show no change in peak flow between wet and dry conditions (Table 4.3). The links where an increase in flow is observed tend to be those on which the speed – flow diagram does not hold. There may be a number of reasons why there is an observed increase in peak flow on some links during precipitation events. It may be that on these links, peak flows are nowhere near the maximum physical capacity of the links and therefore the link does not reach capacity at any point. For example, a link with a peak flow of less than 1000 vehicles per hour is unlikely to

reach the maximum physical capacity of around 6000 vehicles per hour. The links where peak flow increases during precipitation tend to be rural links especially those on the northern stretch of the M6 between junctions 34 and 43. Another explanation may be that some links are simply too short in length to exhibit all the characteristics of the speed – flow diagram and as a result, the speed – flow diagrams for shorter links exhibit very different relationships to the speed – flow diagram. This further reinforces the importance of developing the understanding of how speed – flow relationships vary at a local scale. As such, it appears impossible to apply a generalised model to local sections of the UK road network due to the varying characteristics of each individual link.



(a)



(b)

Figure 4.5 Reductions in speed at the 85th percentile on (a) the northbound carriageway, and (b) the southbound carriageway

Table 4.3 Changes in peak flow between dry and wet weather regression results

Total number of links	138
Links with flow increase in wet weather	58
Links with no change in flow in wet weather	2
Links with flow reduction in wet weather	78
Links with 0% < flow reduction ≤ 10%	46
Links with 10% < flow reduction ≤ 20%	19
Links with 20% < flow reduction ≤ 30%	3
Links with 30% < flow reduction ≤ 40%	4
Links with 40% < flow reduction ≤ 50%	5
Links with flow reduction > 50%	1

4.6 Future Changes

Although the data are non-conclusive for all links, in the vast majority of cases, it is clear that precipitation has an adverse effect on both speed and flow across the UK road network. With future climate projections suggesting there are likely to be changes to precipitation patterns and in particular more instances of heavy precipitation, precipitation will continue to impact adversely on the road network. In addition to this, the number of vehicles on the road is likely to increase in future (Committee on Climate Change and US Transportation, 2008) and subsequently precipitation will affect a

greater number of road users. Previous studies investigating how climate change may impact on mode choices in future suggest that cars are used as a 'rain coat' during heavy precipitation events where people prefer to use their cars for door to door transport instead of using public transport. As such if there are increased instances of heavy precipitation in future, there are also likely to be increased numbers of vehicles on the road during these events (Bocker *et al.*, 2013). Although the use of cars in place of public transport during heavy precipitation events may be most applicable in urban areas, it is likely that this may also apply to the motorway network where, for example, train journeys are of a comparable duration and the use of a car facilitates door to door travel whereas a train journey may require additional modes of transport at one or both ends to and from the station.

With more vehicles on the road during precipitation events, the impacts on the road network are likely to be increased with more vehicles being affected. Where speed and flow are reduced, journey times and delays are increased not only causing inconvenience for travellers but also affecting the transport of goods both nationally and globally which the economy is so heavily reliant on. To minimise the effects that heavy precipitation may have on the road network in the future, there is a need to consider mitigation strategies when new infrastructure is planned or existing road infrastructure is upgraded. This may include altering road specifications to withstand greater traffic volume or improving drainage on road sections which are already vulnerable to instances of surface flooding.

Utilising managed motorways may also help to minimise the impacts of precipitation. Initially implemented on the M42 and then the M6, the system allows speed limits to be lowered to keep the traffic stream moving and the hard shoulder can also be opened as an additional lane. Using the hard shoulder is an advantage in inclement weather as it can increase the capacity of the road during busy periods where overall traffic speeds have been reduced, or it can be used as a replacement lane if one or more lanes have to be closed due to flooding. The system has recently been implemented on the M62 too and is a system which is likely to be employed on an increasing number of motorways in future as an effective means of managing traffic.

With the majority of economic activity being concentrated in the South of England, and the M1 – M6 corridor being vital for transport of people, goods and business from the South to the North, any changes in precipitation which affect transport along this corridor will subsequently have an adverse impact on the economy. With differing amounts of annual precipitation already experienced in different regions across the UK, regions will experience differing degrees of change in precipitation in future and therefore impacts and their severity will also differ. There is likely to be an increased number of intense precipitation events across the UK as a result of climate change, and also a change in precipitation patterns with less rainfall in summer and more in winter. Figure 4.6 shows the central estimate of predicted annual, summer and winter percentage changes in precipitation by the 2080s under the medium emissions scenario, highlighting the potential regional differences.

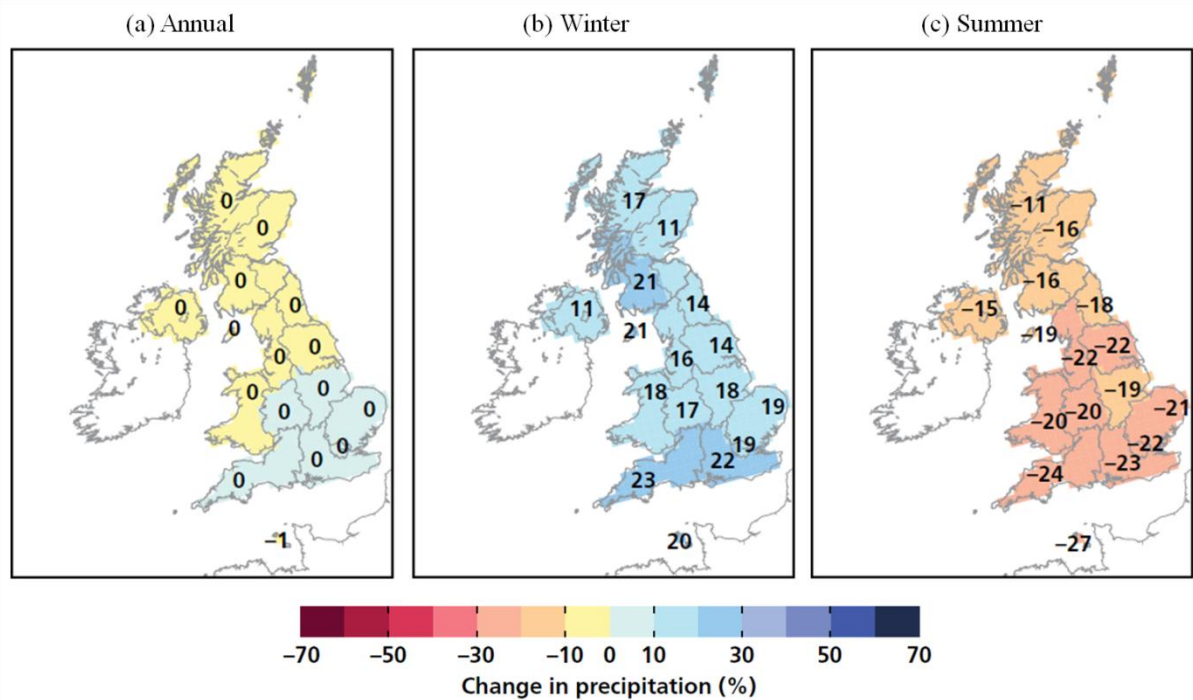


Figure 4.6 Changes to annual, winter and summer seasonal mean precipitation (%) at the 50% probability level by the 2080s under the Medium emissions scenario (Murphy *et al.*, 2009)

Links which are particularly vulnerable to precipitation and experience a large reduction in flow under current weather conditions are likely to endure more severe impacts if there are changes to precipitation in future, particularly an increased number of heavy precipitation events. At the two ends of the route corridor, winter precipitation in London is expected to increase by 19%, but only by 16% in North West England, relative to the baseline climate shown in Figure 2.1. Summer precipitation is less problematic, with a predicted decrease of 22% in both regions (Figure 4.6). Using link LM201 (M1 J1 to J2) at the start of the route in London as an example, this section of motorway has a 40% reduction in traffic flow accompanied by a speed reduction of

2.6% during wet weather. Based on the UKCP09 projections, with an increase in winter precipitation of 19%, the impacts of precipitation during the winter months will be intensified with traffic being affected by precipitation more frequently. Changes in precipitation are likely to cause particular problems on this and subsequent northbound links as it is one of the main routes out of London with high traffic volumes, and likewise there will be similar problems for southbound links into London.

This increase in journey times will in turn increase delay related costs (Hooper & Chapman, 2012). Costs for businesses due to adverse weather are already high. For example, traffic disruption during flood events at peak times is estimated to cost at least £100,000 per hour on any main road affected in the UK (Arkell & Darch, 2006). The projected increase in winter precipitation, and indeed intense summer storms, will mean an increased frequency of precipitation impacts and associated costs. Based on the speed reductions calculated on the corridor (Chapter 3) and the peak flow during a precipitation event from the polynomial regression results in this study, it is possible to calculate an estimate of the cost of a precipitation event on any of the links along the corridor. Delays for an individual vehicle can be calculated by comparing the journey time in wet weather to the journey time in dry weather and this can then be scaled for all vehicles using the peak precipitation flow determined. The delay cost for each link is then calculated using the figure of £100,000 per hour as a basis (Arkell & Darch, 2006).

Table 4.4 provides the results for a selected number of links including the links with smallest (LM1000 – M6 J40 to J41) and greatest delay costs (LM99A – M6 J3A to J3).

There is a clear contrast between rural and urban links. Links with low flows tend to be non-urban and therefore the impacts of precipitation and associated costs are nearly always small (e.g. link LM1000 – M6 J40 to J41). Conversely, links with large delay costs, often in excess of £250,000 per precipitation event, tend to be in more urban locations and consequently have much larger traffic flows to be affected in the event of precipitation occurring e.g. LM999A – M6 J3A to J3. At Junction 3A of the M6, the M6 Toll rejoins the M6 and traffic flows along this section are much higher as a result of the influx of vehicles from the M6 Toll. These costs apply to a single precipitation event on a given link at any time under present precipitation conditions and if there is to be an increase in precipitation during winter then there will be a subsequent increase in costs as the hazard is encountered more frequently by road users.

Currently, London has around 39 days with precipitation each winter (World Meteorological Organisation, 2012). Link LM201 (M1 J1 to J2) has a delay cost of £47,315 per precipitation event (Table 4.4) and assuming it rains at least once on each of these days, the total winter delay cost will be at least £1,845,285. To create an estimate of how cost may be affected in future, the predicted 19% increase in precipitation during winter (2080s, medium emissions scenario) was applied to the current number of days with precipitation, suggesting that there will be 46 days with precipitation and an associated delay cost of £2,176,490. This demonstrates that costs of precipitation events are likely to increase due to climate change and as a result will present further challenges for the economy unless mitigation and adaptation strategies are applied to enable the road network to cope with future changes in precipitation.

Table 4.4 Calculated delay costs for selected links on the route

Link	Start Junction	End Junction	Avg speed (km h⁻¹, no precip)	Avg speed (km h⁻¹, precip)	Link Length (km)	Peak flow during precipitation (no. of vehicles)	Dry time to cross link (hours)	Precip time to cross link (hours)	Delay time (hours)	Total delay (hours, for all vehicles)	Delay cost
LM1000	M6 J40	M6 J41	114.57	114.23	5.16	349	0.0450	0.0452	0.0001	0.05	£ 4,637.06
LM1005	M6 J43	M6 J42	111.39	109.04	4.35	242	0.0391	0.0399	0.0008	0.20	£ 20,298.64
LM1007	M6 J44	M6 J43	111.09	109.22	6.49	302	0.0584	0.0594	0.0010	0.30	£ 30,222.92
LM1021	M6 J9	M6 J10	92.74	86.23	2.42	1289	0.0261	0.0281	0.0020	2.54	£ 254,215.96
LM173	M1 J19	M1 J20	110.89	108.60	5.78	647	0.0521	0.0532	0.0011	0.71	£ 71,047.70
LM201	M1 J1	M1 J2	95.59	93.11	3.72	456	0.0389	0.0400	0.0010	0.47	£ 47,315.17
LM957	M6 J23	M6 J22	100.22	93.09	4.91	1118	0.0490	0.0527	0.0038	4.20	£ 419,669.08
LM998A	M6 J3	M6 J3A	109.63	104.89	13.4	1038	0.1222	0.1278	0.0055	5.74	£ 573,819.88
LM999A	M6 J3A	M6 J3	109.48	103.47	13.28	1054	0.1213	0.1284	0.0071	7.43	£ 743,474.68

4.7 Summary

Whilst the speed – flow diagram is a long established means to model speed and flow on road networks, this study has shown that the approach is perhaps too simplistic with only a third of the links on the corridor conforming to the curve. A number of factors may contribute to the variation in speed – flow relationships on the links studied including lane closures, road works, weather, exceptionally high traffic volumes and driver behaviour. Light conditions may be another impacting factor; the relationship observed in daylight may be different to that observed during darkness and this could be an area for further investigation. In most cases, it is the relationship at low flows (i.e. congestion) which causes the largest deviations from the diagram. This effect was also observed by Van Aerde & Rakha (1995) who attributed the problem with low flows to an insufficient number of events in the analysis to constrain the curve. Indeed, this is a known issue with the HATRIS data as both low and stationary flows are often treated as errors in the algorithm and subsequently are automatically corrected without record. For links where the speed – flow diagram holds, the impact of precipitation is evident and particularly acute in urban areas. In the majority of cases, speed and maximum flow are reduced when precipitation occurs. However, these impacts are very much specific to the individual links, with all links having slightly different relationships characterised by individual maximum flows and critical speeds. This reinforces the need to improve understanding of how weather conditions affect traffic operations at a local scale.

Current UK climate change projections indicate increased winter precipitation as well as a greater frequency of intense summer events. The impacts on speed and flow observed

in this study are central to building knowledge of how the road network may be affected in the future. This will provide the information required as to how networks could be adapted to cope, as well as starting to understand what the knock on effects may be for the economy. However, whilst the results of a study such as this may be used to determine how road transport may be affected by similar precipitation in future, it is important to remember that climate is not the sole variable needing consideration, but also society and the economy. Transport's vulnerability to weather and climate has already changed during the past 50 years and the associated costs have risen (Jaroszweski *et al.*, 2010), so it is expected that future impacts of weather and climate will differ from those observed currently. To address this, it is important also to consider future scenarios which indicate what society may be like based on values and governance (e.g. Connor, 2001). After all, in another 50 years, the economy is likely to need a surface transportation network unrecognisable to the one in place today.

Chapter 5 - Quantifying the Operational Impact of Traffic

Accidents during Precipitation on a Motorway Corridor

5.1 Introduction

Weather is a significant factor contributing to the occurrence of road traffic accidents. Whilst weather alone is unlikely to be solely responsible for an accident, it remains a significant risk factor. Indeed, the overall impact of weather conditions depends on a number of factors including not only the time and duration of the event but also how recently the weather has previously been experienced by road users (Eisenberg, 2004). Precipitation is consistently a hazard for the road network and its users (Keay & Simmonds, 2006), and consequently precipitation poses a frequent hazard for road safety. Indeed, around 15% of road accidents in the UK occur during precipitation events (where accident records indicate that rain occurred at the time of the collision; Edwards, 1998) and it is assumed that any change in precipitation will alter overall accident risk.

Whilst 15% of accidents occur during rainfall, rainfall occurs less than 15% of the time in the UK. Therefore, the number of accidents occurring in wet weather is disproportionate to the amount of time that it rains. As accidents pose a serious problem for the safety of road users, there is a need to better understand how weather impacts upon accident risk to enable more effective road management and driver education using the knowledge gained from investigating current weather impacts on road traffic

accidents. The objective of this chapter is to investigate road traffic accidents along a UK motorway corridor, investigating how traffic is affected by accidents occurring in wet weather. The results obtained are used to determine the resilience of the corridor in terms of impacts on traffic speed, flow and recovery times. This work then continues by predicting how road traffic accident numbers may be affected in future as a result of changes in precipitation due to climate change.

5.2 Background

5.2.1 Precipitation and Road Traffic Accidents

Table 5.1 provides a summary of studies which have investigated the relationship between precipitation and road traffic accidents, highlighting the variation in accident numbers and risk across a number of countries. As with research into the impacts of precipitation on traffic parameters in the UK, there are few studies which examine how accidents are affected by precipitation. Those which have identify that around 15% of all traffic accidents occur during rainfall and wet days are associated with higher accident numbers than dry days (Smith *et al.*, 1982). One interesting finding is that accident severity decreases during rainfall, when compared with dry weather, i.e. a greater proportion of accidents are recorded as slight severity as opposed to fatal or serious severity (Edwards, 1998). Overall, there is a general consensus that accidents in wet weather are more frequent yet less severe than in fine, dry weather which could reflect lower traffic speeds (Edwards, 1998), but the full impact of precipitation on road

safety needs further investigation and the relationship needs to be quantified for use in climate change risk assessments.

As with many areas of road transport research, the majority of studies are focused on North America, with just a handful examining the impacts in Europe, and in particular the relatively benign climate of the UK. Across the literature, it is acknowledged that the number of accidents is elevated when precipitation occurs (Andreescu & Frost, 1998; Andrey *et al.*, 2003; Golob & Recker, 2003). However, due to the varying nature of precipitation, accident characteristics vary with precipitation type (Andrey *et al.*, 2003) with accidents in snow generally being more severe than in rain. Hence, there is a need to interpret existing studies carefully. While precipitation causes the number of accidents to increase, the severity tends to be less than those occurring in dry weather. This could be interpreted as a change in driver behaviour in line with the conditions, resulting in lower speeds during wet weather (Koetse & Rietveld, 2009). Indeed, such a reduction in speed during precipitation events has previously been observed (Chapters 3 and 4), although there is presently little research to suggest that this is actually a direct result of drivers taking more care during precipitation events (Edwards, 1998).

Table 5.1 Summary of results from previous studies investigating the impact of precipitation on traffic accidents

Authors	Location	Findings
Andrescu & Frost (1998)	Montreal, Canada	Positive correlation between accidents and rainfall
Andrey <i>et al.</i> (2003)	Canada	Precipitation associated with 75% increase in collisions; 45% increase in related injuries Risk levels vary depending on characteristics of the weather event
Andrey (2010)	Canada	Positive association between precipitation intensity and casualty risk Combinations of conditions are problematic – for example heavy traffic coupled with precipitation
Brijs <i>et al.</i> (2008)	Netherlands	Higher rainfall intensities lead to a higher number of crashes Positive relationship between number of hours of rainfall per day and number of crashes Weekdays are more dangerous than weekends
Brodsky & Hakkert (1988)	Israel and US	Added risk of injury in rainy conditions can be substantial – 2 to 3 times greater than in dry weather Hazard is greater when rain follows a dry spell
Edwards (1998)	UK	Accident severity decreases significantly in rain, compared with fine weather In both fine and wet weather there seems to be a distinction between accidents in urban and rural areas
Edwards (1999b)	UK	Cyclic nature of accidents recorded in adverse conditions shows remarkable similarity to the occurrence of the hazards demonstrating the close association between weather related monthly accident totals and weather hazards
Eisenberg (2004)	US	Significant negative relationship found between monthly precipitation and fatal crashes i.e. fewer fatal accidents in wetter months At a daily level, strong positive relationship found Risk imposed by precipitation decreases dramatically as the time since last precipitation increases
Golob & Recker (2003)	US / Canada	Crash rates are elevated by precipitation, accident characteristics vary by weather type Evidence that accident severity is influenced more by volume than speed
Hermans <i>et al.</i> (2006)	Netherlands	Precipitation has the most impact of all the weather indicators Impact of precipitation duration seems greater than precipitation amount
Keay & Simmonds (2006)	Australia	The presence of rainfall consistently presents a hazard for driving Impact after a dry spell is greater as both the dry spell duration and the rainfall amount increase
Mills <i>et al.</i> (2011)	Canada	Rainfall is associated with large increases in collisions and injuries
Smith (1982)	Glasgow, Scotland	Rain is the most common hazard affecting the UK, around 15% of all accidents occur in this weather Wet days are associated with higher number of accidents, especially in summer

Both precipitation intensity and precipitation duration have an effect on the number of accidents, particularly duration – the longer the rain event, the greater the number of accidents that occur (Brijs *et al.*, 2008; Hermans *et al.*, 2006). Indeed, Hermans *et al.* (2006) concluded that precipitation duration seemed to have a greater impact on the number of accidents occurring than precipitation intensity, with ten extra minutes of precipitation increasing accident numbers by an average of 6.5%. Water depth on the road surface also needs to be considered, as effects such as ‘aquaplaning’ are a cause of increased accident numbers in wet weather (Veith, 1983, in Andreescu & Frost, 1998). Drainage problems are frequently evident during heavy precipitation events, particularly convective summer storms (Andreescu & Frost, 1998), and will have implications for the amount of surface water on roads as well as visibility. Finally, the frequency with which precipitation occurs also impacts on the risk of an accident occurring – the longer it is since precipitation last occurred, the greater the risk posed when precipitation does occur, often due to the build up of oil on the road surface during the dry period which causes the surface to become slippery when mixed with precipitation (Eisenberg, 2004; Keay & Simmonds, 2006).

The exact timing of accidents needs careful consideration due to inherent variations in traffic volumes at a range of temporal scales. Andreescu & Frost (1998) observed that whilst there was a clear positive relationship between rainfall and accident numbers in the summer months, the relationship varied in winter with larger numbers of accidents on days with low rainfall totals whereas fewer accidents occurred on days with larger rainfall totals. Again, this may be related to driver behaviour and in particular the impact of weather on driver choices as drivers may shift mode or postpone a trip during

heavier precipitation events (Koetse & Rietveld, 2009). Urban / rural distinctions are also clear with rural areas having more severe accidents in both wet and dry conditions than urban areas which may be due to lower traffic densities on rural roads allowing drivers to travel at greater speeds than in urban areas (Edwards, 1998). Accident numbers are also affected by the presence of bends in the road (Taylor *et al.*, 2002) and as urban roads tend to be straighter than rural roads, this may be a factor in the distinction between accident numbers. There are large geographical differences in casualty numbers and severities across England and Wales (Jones *et al.*, 2008), and so accidents are likely to be affected by local weather conditions.

Driver behaviour during adverse weather conditions will also impact on accident risk and frequency. Lower speeds observed in wet weather conditions (Koetse & Rietveld, 2009; Hooper *et al.*, 2012) suggest that drivers are aware of the need to adapt their driving accordingly and many do indeed reduce their speed in wet weather when friction with the road surface is reduced and stopping distances are increased. Although drivers may be aware of the impact of wet weather, drivers need encouragement to adapt their driving conditions based on the weather conditions at the time (Edwards, 1998). This could be carried out by imposing lower speed limits along sections of carriageway which use variable speed limits. Another approach may be to impose lower speed limits which must be adhered to when it rains, similar to France where the maximum speed limit is lowered by 10 km h⁻¹ when it rains.

Better utilisation of variable message signs which are already in place on the motorway network to advise drivers of adverse weather conditions and the action they should take would be highly beneficial (Edwards, 1998). Several types of variable message signs are used in the UK (Variable Message Signs, 2013). Matrix signs are the simplest, displaying numbers or indicating if a lane is closed and can be used to advise drivers of a lower speed in inclement weather. Electronic variable message signs can display messages consisting of both text and numbers including 'Incident – slow down' or 'Spray – slow down'. Advanced Motorway Indicators are the most recent type of variable message signs installed and are often used on stretches of managed motorways. These can display more detailed information including speed limits, lane closures and longer messages about incidents and weather conditions. All can be used in inclement weather and should be used more proactively to advise drivers of action to take. Where drivers adapt their behaviour by reducing their speed accordingly and driving with more caution, then some of the risk associated with adverse weather conditions is eliminated (Andrey *et al.*, 2003). Using variable message signs to try and enforce these reductions may help to reduce the risks associated with wet weather.

5.2.2 Climate Change and Road Traffic Accidents

Whilst there is an extensive body of literature into the impacts of current weather conditions on accident frequencies and severity, research into the potential impacts of climate change is limited. However, in light of the projected changes in precipitation, it is important to consider how road traffic accidents may be affected in order to prepare for any future changes to accident severity and number. All accidents impact the traffic

stream as a whole causing delays, prolonging journey times and in the most severe cases resulting in road closures (i.e. a total failure of part of the network). It is assumed that any current impacts of precipitation on road traffic will continue into the future under similar weather conditions, and will rise or fall in line with changes in precipitation patterns (e.g. more heavy precipitation events).

Hambly *et al.* (2013) is one of the few studies to actually consider how road safety and traffic accidents may be affected in future as a result of a changing climate. The findings are that precipitation is envisaged to have the greatest adverse impact, particularly on days with moderate to heavy rainfall ($\geq 10\text{mm}$). In particular, any changes in intensity and frequency of extreme precipitation events will need attention as collision risks will change and most likely increase, unless there are alterations to safety measures for the road network. Although the study focuses on the effects of climate change in Greater Vancouver, it raises some important points about the implications of changing precipitation patterns for road safety acknowledging that the impacts will be specific to individual locations. The importance of detailed micro level analysis is highlighted due to its ability to consider local weather conditions and how they impact on local collision risks. Areas which are projected to experience more frequent or heavier rainfall are also likely to be the areas where more rainfall crashes occur (Hambly *et al.*, 2013). In contrast, climate change may have some advantages for road safety with a reduction in the number of UK frost days during winter likely to reduce accidents caused by slipperiness by around 50% (Andersson & Chapman, 2011).

However, the projection of accident numbers decades into the future can be problematic. There has been a downward trend in total accident numbers (in all weather conditions) during the past 20 years which can mostly be attributed to improvements in vehicle safety and technology (Edwards, 1996; Andrey, 2010). It is therefore likely that continued improvements to technology will help to reduce both accident numbers and risk further into the future. However, vehicle safety improvements alone are unlikely to eliminate totally the risk of accidents and so weather will still play an important role in the occurrence of accidents in future.

5.3 Speed and Flow

5.3.1 Method

Although motorways are considered to be among the safest roads across the UK due to the elimination of oncoming traffic, junctions and roundabouts (Edwards, 1999a), a number of severe accidents still occur across the network. Motorway accidents occurring can be particularly severe and in some cases there are multiple fatalities, one such example being the accident on the M5 at Taunton on 4th November 2011. Factors external to the motorway were deemed to be the influencing factor in this case, with smoke from a bonfire party at a nearby rugby club drifting across the carriageway and seriously reducing visibility. Jack knifing of lorries is a motorway specific hazard which can lead to severe accidents and is often a problem specific to individual sections of the motorway network (e.g. the M6 between junctions 15 and 16.)

To investigate how accidents during precipitation events impact on traffic speed and flow, accidents along the route corridor are investigated utilising two data sets. STATS19 is the national database containing information about accidents severe enough to be reported to the police (i.e. where an injury has been sustained). A wealth of information is contained in the database about each individual accident including the location, time, date, weather conditions and road surface conditions amongst others. Due to the severity of traffic accidents on the motorway, it is likely that every accident will be reported to the police and therefore STATS19 is a comprehensive data set suitable for use in this study. The STATS19 database has been used in a number of previous studies (Andersson & Chapman, 2011; Edwards, 1996; Edwards, 1999b; Jones *et al.*, 2008; Wang *et al.*, 2009) and so is appropriate to use in this study. Accidents for analysis were identified using the STATS19 weather indicator. Any accidents where the prevailing weather condition at the time was classified as '*rain, no high winds*' or '*rain, high winds*' were selected for analysis. As the surface condition can also be a contributing factor, accidents where the surface condition was classified as '*wet or damp*' were also selected.

Traffic speed and flow data from the Highways Agency Traffic Information System (HATRIS) were also used allowing for identification of any changes to traffic parameters throughout the day. This study utilises the data to identify the local impacts of accidents at a high temporal resolution giving a detailed picture of the impacts of wet weather traffic accidents on the road network. Accidents occurring during 2008 were investigated due to this being the first full year for which HATRIS data are available. Once the location, date and time of an accident was identified, speed and flow data from

HATRIS were plotted, allowing for identification of the reductions in speed and flow following the occurrence of the accident.

5.3.2 Results and Discussion

Whilst the majority of accidents along the route corridor occur in dry weather, 15% of the accidents in 2008 occur when it is raining and 30% occur when the road surface is wet or damp (concurring with the findings of Edwards, 1998). There is a relatively even distribution of accidents along the route throughout the year. Figure 5.1 and 5.2 show the number of accidents per link along the route occurring during precipitation events on the north and south bound carriageways respectively. The number of accidents on wet / damp road surfaces of the north and south bound carriageways are shown in Figures 5.3 and 5.4.

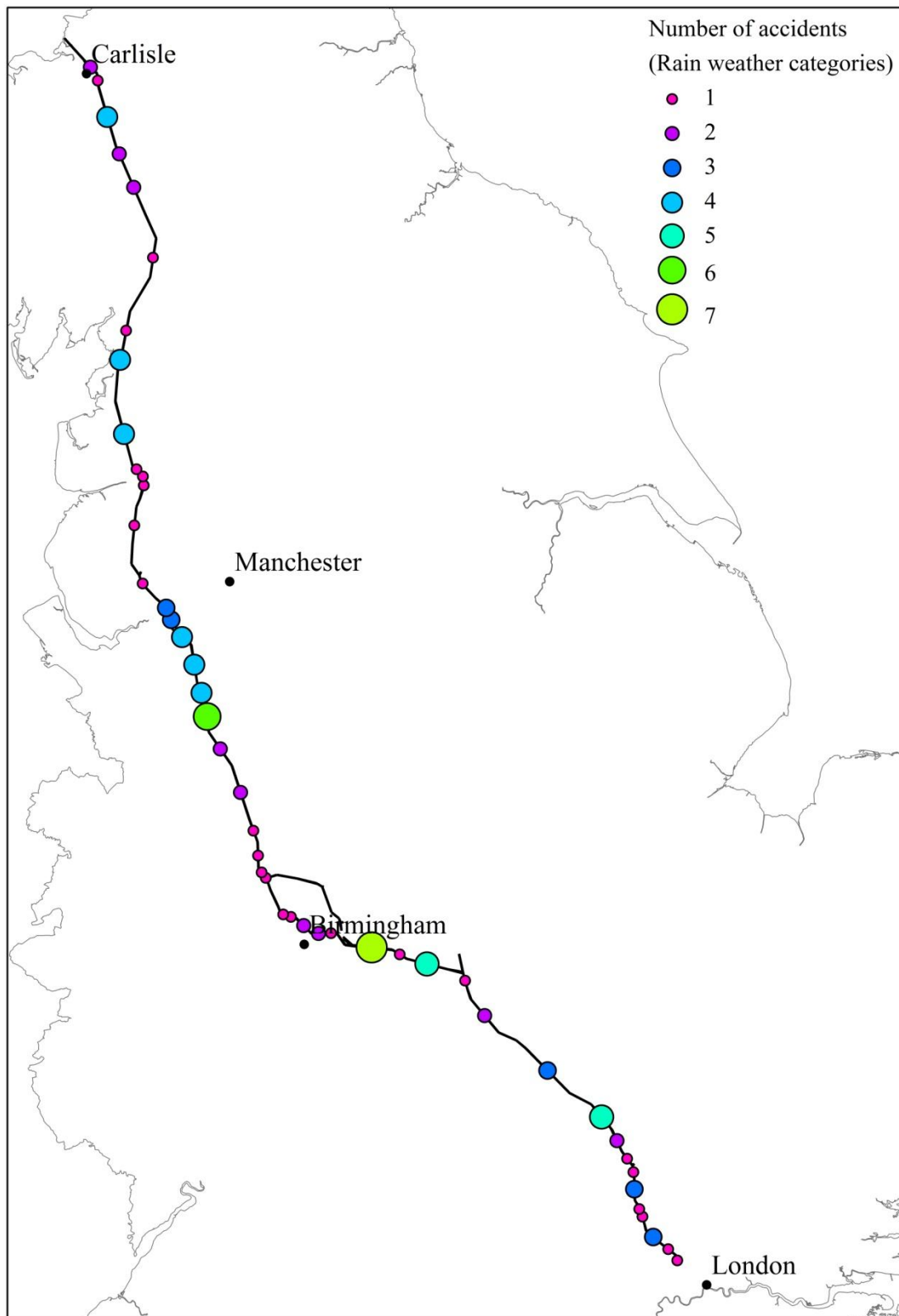


Figure 5.1 Accidents along the northbound M1 and M6 route where the prevailing weather condition at the time of the accident was rain (total number of accidents = 103)

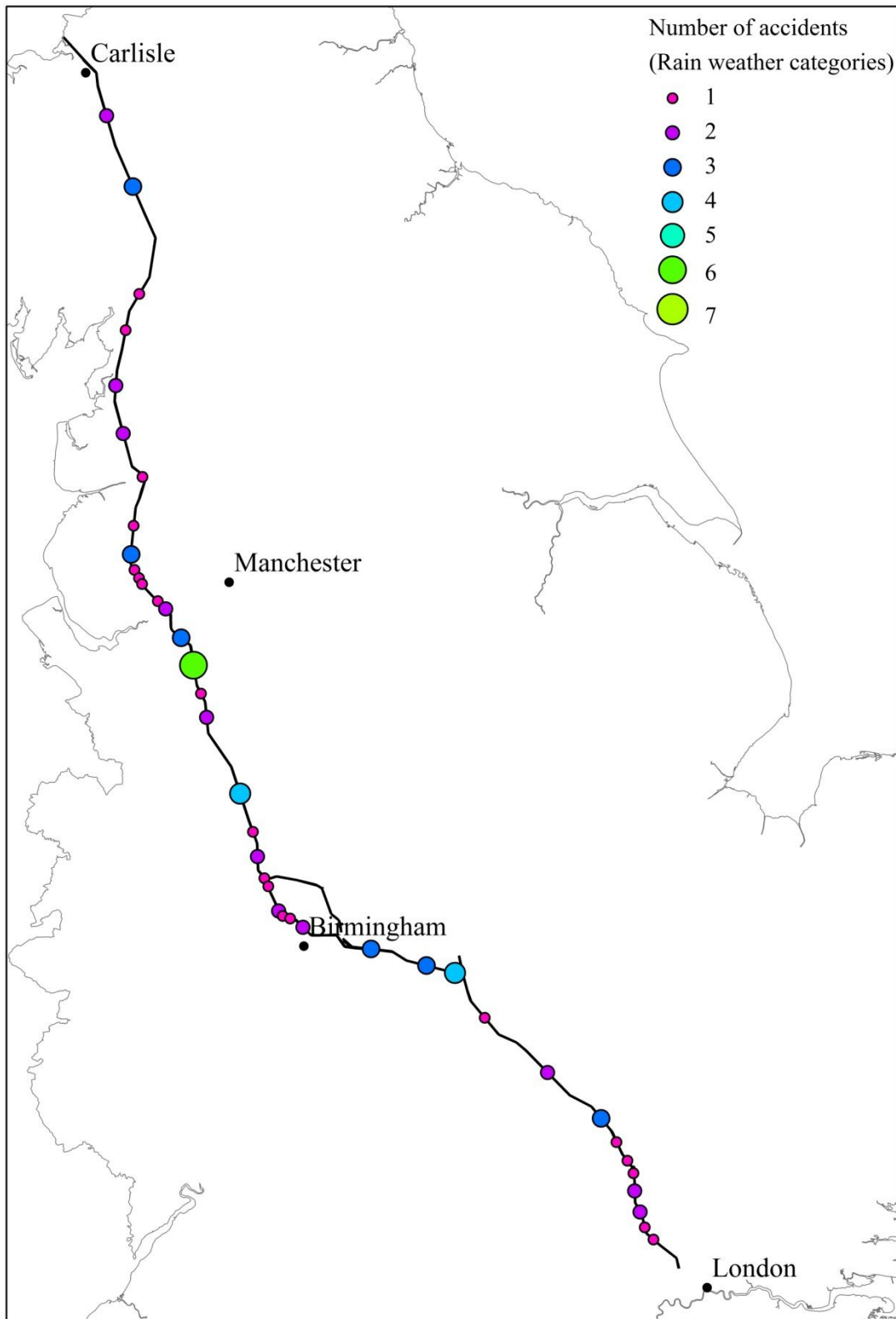


Figure 5.2 Accidents along the southbound M1 and M6 route where the prevailing weather condition was rain (total number of accidents = 74)

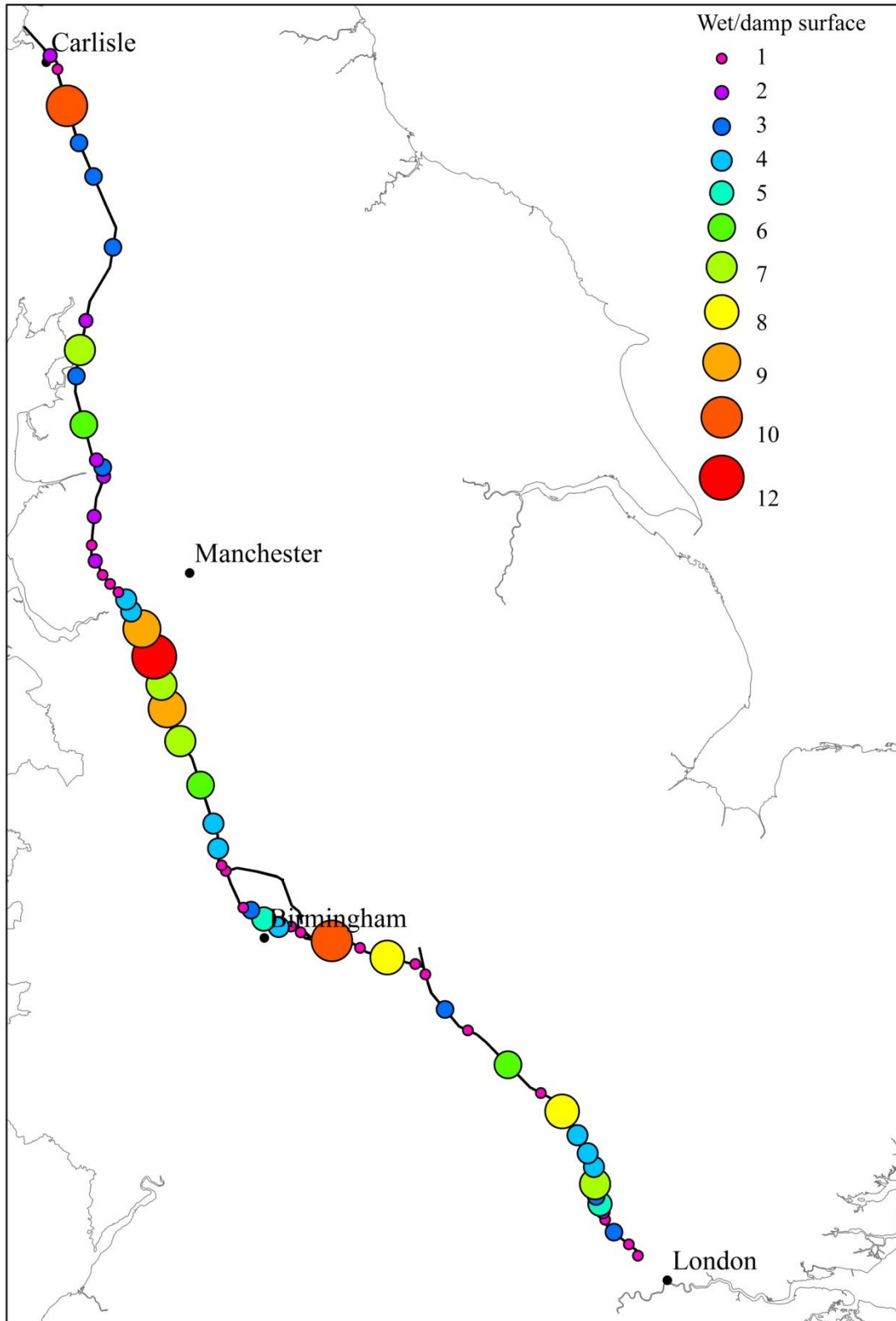


Figure 5.3 Accidents along the northbound M1 and M6 route where the road surface was wet or damp (total number of accidents = 213)

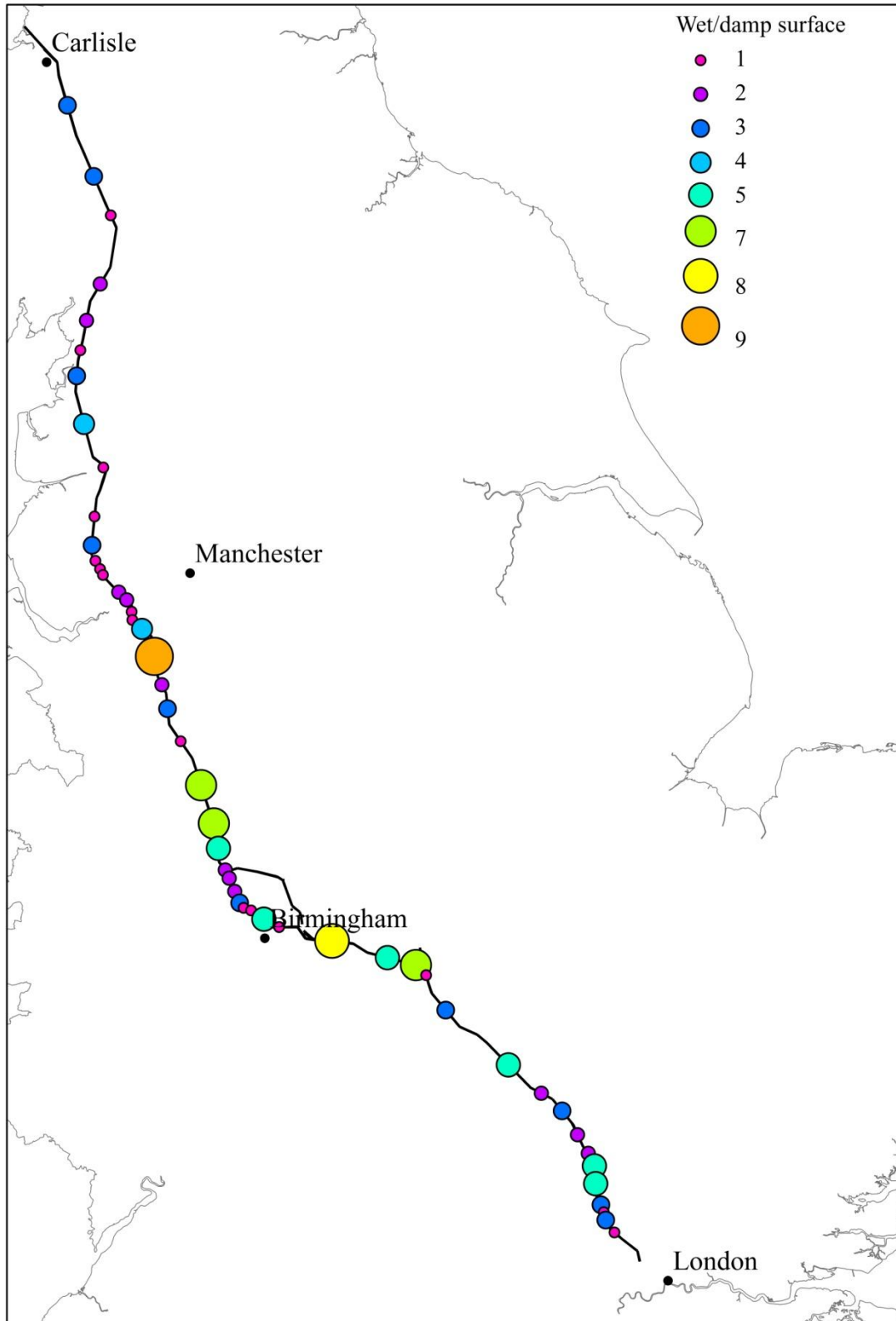


Figure 5.4 Accidents along the southbound M1 and M6 route where the road surface was wet or damp (total number of accidents = 144)

It was hypothesised that the links which are the wettest, i.e. have the greatest annual rainfall totals, would have the greatest number of accidents in wet weather. However, on examination of the locations of the links with the greatest number of accidents in wet weather, it appears that this is not the case and these links are spread out across the route. The northern section of the M6 through Cumbria has some of the greatest rainfall totals (Figure 2.1) and is one section where greater accident totals would be expected. However, from the data, the number of accidents occurring along this section in wet weather is far less than along many drier sections of the route, a consequence of the lower volume of traffic on this link. Peak traffic flow and average annual rainfall for each link on the northbound route are shown in Figure 5.5, where it is evident that traffic flows on the M6 throughout Cumbria are lower than on the majority of the other route links.

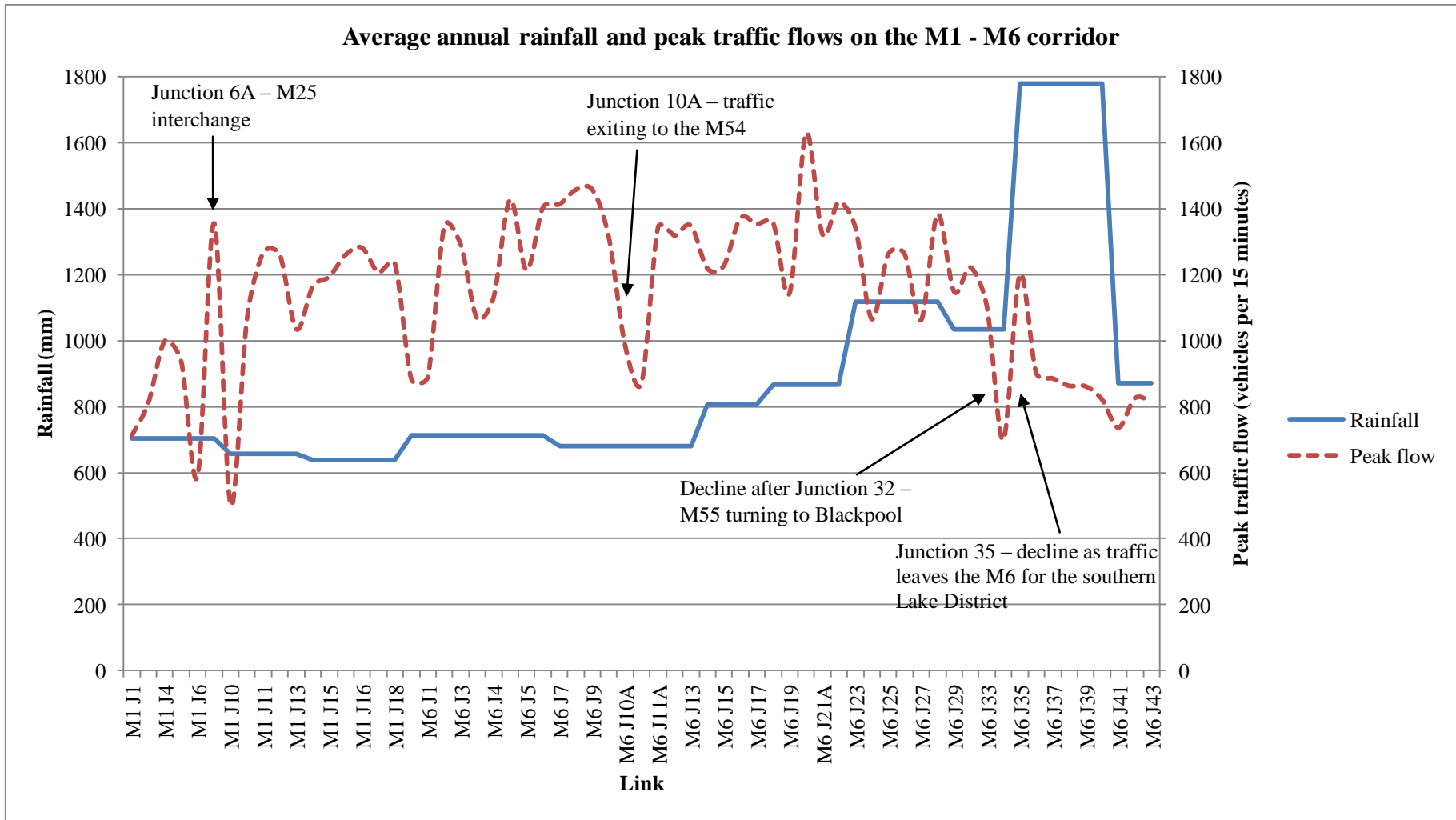


Figure 5.5 Average annual rainfall and peak flow values for northbound links on the route

It appears that traffic flow volumes have a strong influence on the number of traffic accidents occurring. Links which have higher traffic volumes tend to have a greater number of accidents in wet weather. One such example is at junction 4 of the M6. Here there is an increase in traffic volume due to the influx of vehicles from the M42 with the peak flow on this link being around 400 vehicles greater than on the previous link (Figure 5.5). The number of wet weather accidents at this point on the northbound carriageway is consistently higher than on surrounding links as shown in the accident maps (Figures 5.1 and 5.3).

For the majority of accidents which occurred during wet weather or when the surface was wet / damp, there is a reduction in speed and a subsequent reduction in traffic flow across the link. Figure 5.6 shows one such accident and the reductions in speed and flow just after the accident occurs, as well as the recovery of the traffic stream to the average speed for the link. There are, however, some instances where traffic speeds appear to be unaffected following an accident and the recorded speeds stay well above the average free flow speed for the link.

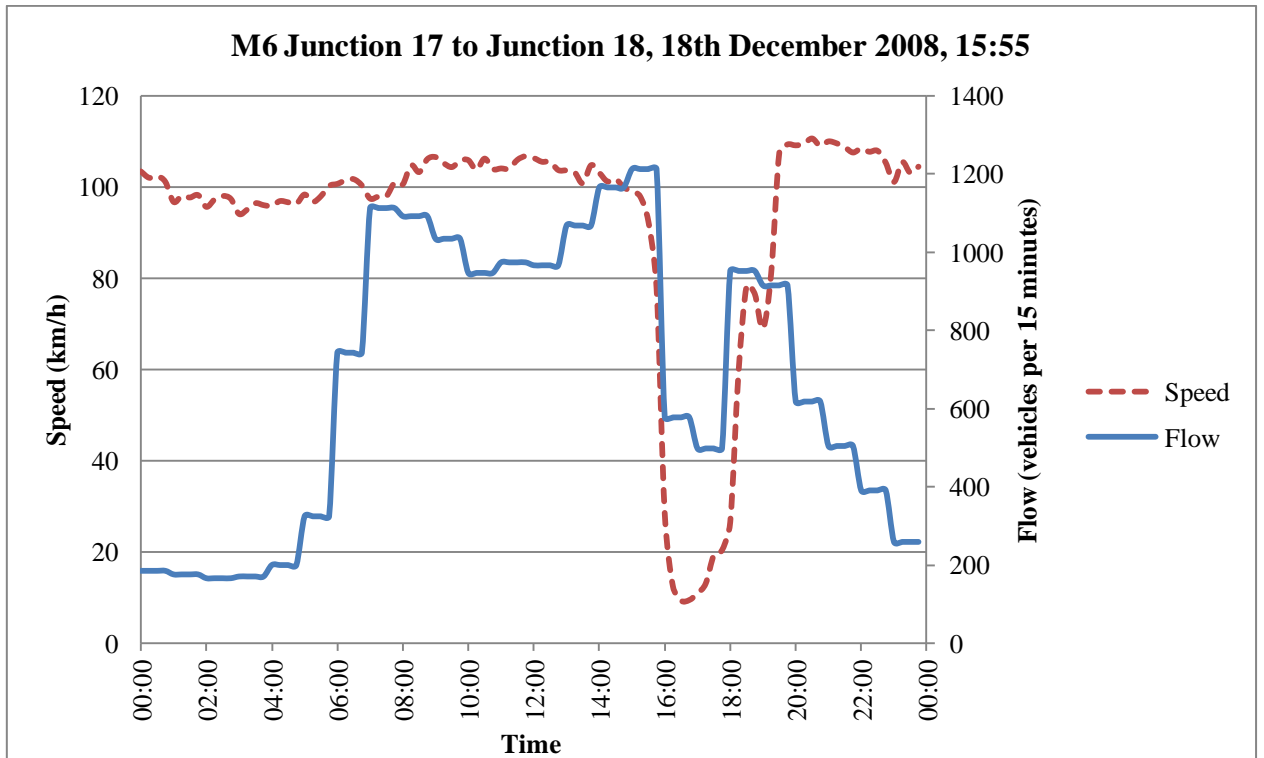


Figure 5.6 Speed and flow on 18th December 2008, M6 junction 17 to junction 18 – accident occurring at 15:55 (raining, high winds)

Although accidents occurring in wet weather during 2008 appear to be evenly spread along the route corridor, there are several points along the route where there are a higher number of wet weather accidents, particularly between junctions 15 and 19 of the M6, and also between junctions 41 and 42. On the M1, the highest numbers of wet weather accidents occur between junctions 12 and 13. The majority of links with the greatest numbers of wet weather accident numbers tend to have a peak vehicle flow of between 3600 and 4800 vehicles per hour, although there are two links which have lower peak flows of between 1600 and 2800 vehicles per hour. Where there are very few or even no wet weather accidents (either occurring during rainfall or on a wet / damp surface), the

links tend to be in more rural locations where traffic flows are lower than on links which have high numbers of wet weather accidents.

Where accidents occur in wet weather or on a road surface that is wet / damp, a reduction in both speed and flow is evident in the majority of cases. The magnitudes of reductions vary greatly with a greater reduction in speed being associated with more severe accidents. The number of vehicles involved in the accident also impacts on the severity of the reduction in both speed and flow – the more vehicles involved, the more likely it is that a larger portion of the carriageway will be blocked and therefore, fewer lanes will be available for vehicles. Whilst it appears that the most severe accidents have the greatest reduction in speed, there are some instances where the reduction in both speed and flow is far less than expected. Unfortunately, where the motorway is stationary or has to be closed, the HATRIS data is infilled with historical data and this may be the cause of less than expected reductions in both speed and flow. For example, an accident occurred between junctions 8 and 9 of the M1 on 31st August 2008 at 12:12pm and the speed does not fall below 50 km h⁻¹ despite the accident involving eleven vehicles and having eleven reported casualties – a much greater impact would be expected. As such, the impact of some more severe accidents is omitted from the analysis due to the nature of the data.

The severity of accidents occurring in dry and wet weather was also compared. With previous studies identifying that the number of slight severity accidents tends to increase slightly in wet weather (Koetse & Rietveld, 2009), it would be justified to

expect the same to apply along the M1 – M6 route corridor. However, on inspection of the distribution of accidents across the three severity classes of fatal, serious and slight, it is apparent that there is no marked difference in the distribution of accident severity between dry and wet weather, as shown in Table 5.2. There is a very minimal increase in the percentage of accidents which have a slight severity on wet road surfaces compared to on dry surfaces and a small decrease in accidents of fatal and serious severities was observed. This suggests that along the M1 – M6 route, there is little difference in accident severity between dry and wet weather.

Table 5.2 Percentages of accidents classed as fatal, serious or slight in each of the dry and wet weather and road surface categories

	Fatal	Serious	Slight
Fine weather	2.41%	11.26%	86.32%
Wet weather	2.41%	10.84%	86.75%
Dry surface	2.59%	11.04%	86.38%
Wet surface	2.45%	9.48%	88.07%

5.4 Recovery Times

5.4.1 Method

Where speed and flow values are reduced following an accident in wet weather, a recovery time was calculated to identify when speed returned to the average link speed. In each case, the average accident recovery time was calculated and compared to the average recovery time for fine weather and dry road surfaces to determine how rainfall affects the recovery time.

5.4.2 Results and Discussion

The calculated recovery times for wet weather accidents vary greatly. Some accidents have a significant impact (e.g. the M6 southbound between junctions 10 and 9 on 27th November 2008, recovery time = 15 hours 15 minutes) whereas some have very little impact with the traffic stream continuing at free flow speed. Table 5.3 shows the average recovery times for each accident category studied. When compared to the corresponding fine weather category, it is evident that there is an increase in average recovery time following an accident occurring in wet weather conditions. Likewise, the average recovery time increases for accidents occurring on wet or damp road surfaces compared to the average recovery time when the road surface is dry. This may be due to increased stopping distances on wet road surfaces as a result of reduced friction between tyres and the road surface. Another possible cause may be drivers failing to adapt their driving appropriately to respond to the adverse weather conditions. However, the standard deviation for each of the categories investigated is very large and indicates the

range of other factors that play a part in the severity of an accident (i.e. location on the highway, number of vehicles etc).

Table 5.3 Average accident recovery times

	Average Accident Recovery Time	Standard Deviation (minutes)	Number of Accidents
<i>Weather Conditions</i>			
Fine	1 hour 42 minutes	100	416
Rain	2 hours 36 minutes	164	93
<i>Surface Conditions</i>			
Dry	1 hour 37 minutes	88	349
Wet / damp	2 hours 22 minutes	148	174

To test whether the difference between the accident recovery times in dry and wet weather is statistically significant, a Wilcoxon test was used. The data are not normally distributed and so the non parametric Wilcoxon test is more suitable for use here than a parametric *t*-test. The results of the test for the weather categories are shown in Table 5.4 and the results for the surface categories are shown in Table 5.5. In both instances, the mean rank is higher in wet weather and on wet / damp surfaces than in dry conditions and so recovery times in wet weather are greater than in dry weather, reinforcing the results in Table 5.3. Both tests are significant at the 99% level and so it can be concluded that the differences between the average recovery times are significant.

Table 5.4 Wilcoxon test results for accident recovery times in the weather categories

Ranks			
	Number	Mean Rank	Sum of Ranks
Dry	416	244.72	101804.00
Raining	93	300.98	27991.00
Test Statistics			
Wilcoxon		101804.000	
Asymp. Sig. (2 tailed)		0.001	

Table 5.5 Wilcoxon test results for accident recovery times in the surface condition categories

Ranks			
	Number	Mean Rank	Sum of Ranks
Dry surface	349	245.17	85566.00
Wet/damp surface	174	295.75	51460.00
Test Statistics			
Wilcoxon		85566.000	
Asymp. Sig. (2 tailed)		0.000	

There is a clear distinction between the distribution of recovery times in dry and wet weather (Figure 5.7). In both dry weather conditions and on dry road surfaces, the recovery times are bi-modal. There are a large number of accidents with short recovery times (less than 60 minutes) and these are likely to represent the more common, and less severe, 'shunt' type accidents. However, there are also a large number with extensive recovery times of more than four hours. These accidents are likely to be the most severe, causing lane or even entire road closures. The recovery times for accidents occurring in wet weather and on wet road surfaces have a far more erratic distribution with no clearly defined peaks in any one recovery time category. The standard deviations for each category are very large due to the huge range of recovery times which occur. This is particularly true of both the wet weather and wet surface categories where there is a far greater spread of data which is likely to be due to the individual nature of each accident occurring in wet weather – there is no uniform rule which can be applied to accidents occurring under these conditions.

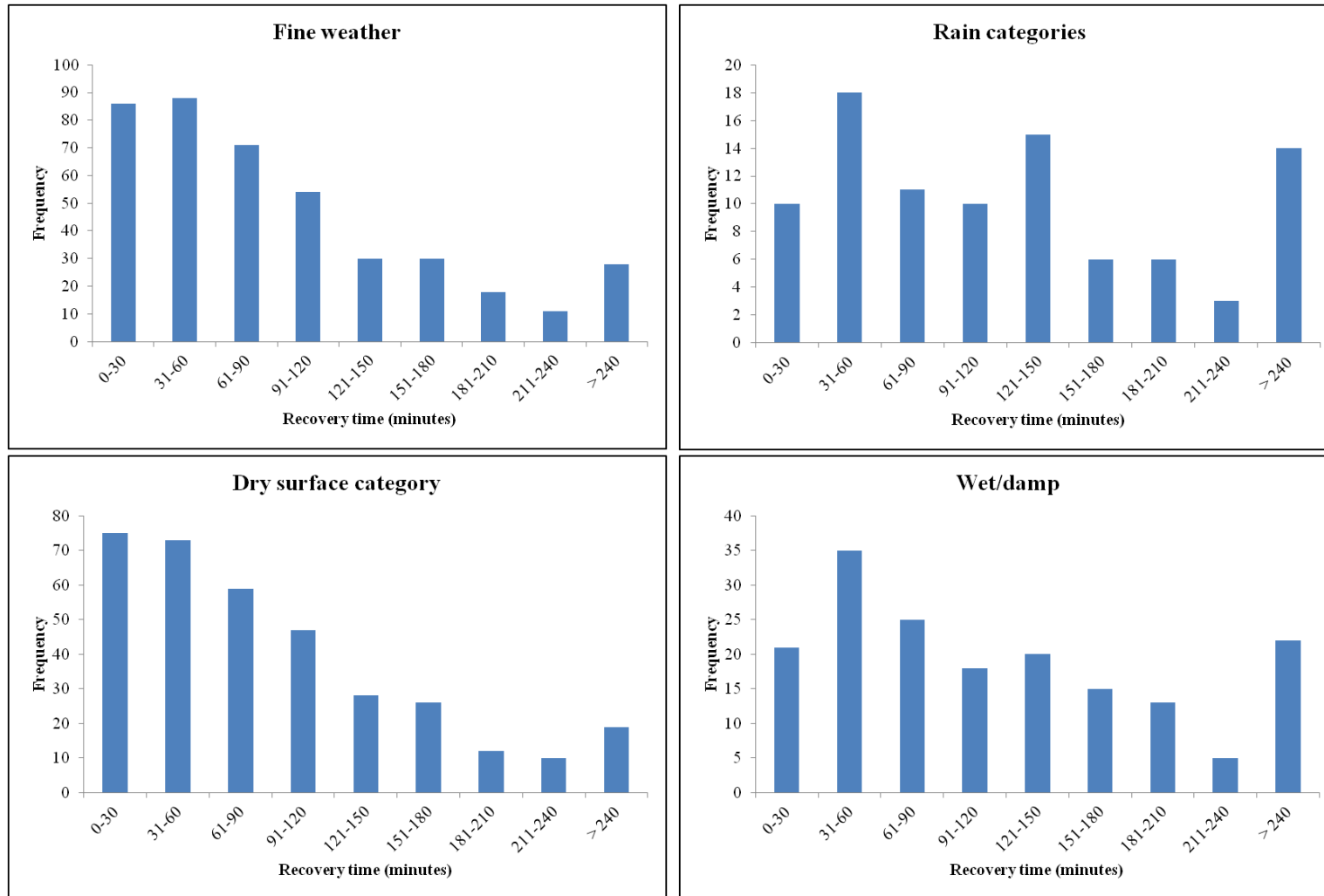


Figure 5.7 Histograms showing distribution of accident recovery times for each weather and surface conditions category studied

5.5 Climate Change

5.5.1 Method

To approximate how accident numbers may change in future as a result of climate change, projected future numbers of wet weather accidents were calculated using the predicted percentage change in precipitation from UKCP09. Ten years of accident numbers (2000 – 2009) are used to provide a representation of the potential number of accidents over a similar time period in future. There has been a decrease in accident numbers in recent years due to improvements in both vehicle and road safety. It is difficult to forecast exactly how accident numbers may be affected by such improvements in future and therefore the accident numbers for 2000 – 2009 are used as a starting point and it must be acknowledged that the forecasts created here do not take into account the effect that safety improvements may have. For each accident category (rain; wet / damp surface conditions), the corresponding percentage increase or decrease in precipitation is applied to the accident categories. With a likely increase in precipitation in winter and a decrease in summer, accident numbers are expected also to follow this pattern with the increase in accidents in winter being offset by a decrease in accidents during the summer.

Whilst this method provides a simple projection of future wet weather accident numbers, it does not account for the potential for increases in accident numbers due to extreme, unexpected weather events which may occur as a result of climate change. Long term trends indicate that road traffic is increasing and is likely to continue to

increase in future (Committee on Climate Change and US Transportation, 2008). Traffic on UK motorways has increased steadily in recent years and in 2012 traffic volumes increased by 1% (Department for Transport, 2013a). The accident forecasts presented here do not consider growth in traffic volumes as they are only very simple forecasts using present day accident statistics and future predictions of changes in precipitation. Predicting exactly how traffic volumes will increase in future relies on a range of factors including fuel prices, changes in the economy and changes to the cost of public transport and as a result cannot easily be included in the simple forecasts created here. The approach used here offers a simple forecast in an attempt to begin to illustrate what the consequences of a changing climate may be for accidents occurring in wet weather conditions.

5.5.2 Results and Discussion

There is a clear relationship between rainfall and the number of traffic accidents – the greater the rainfall total, the larger the number of accidents is. At present, the largest number of accidents in wet weather occurs during the autumn months and on wet / damp surfaces during the winter months (Figure 5.8). As climate projections suggest that winter is the season most likely to experience an increase in precipitation, it is reasonable to assume that there will be a far greater number of accidents due to wet weather in these months. Conversely, summer has the least wet / damp surface accidents of all the seasons and this value is likely to decrease further as a result of decreased summer precipitation in future. The seasonal accident numbers determined from the analysis for 2000 to 2009 were used to create simple projections of changes in accident

numbers in wet weather using the UKCP09 projections for the 2080s, as shown in Figure 5.9. The results show that a much greater number of accidents are likely to occur in winter as precipitation increases, yet in summer the reduction in precipitation is likely to be accompanied by a decline in accident numbers.

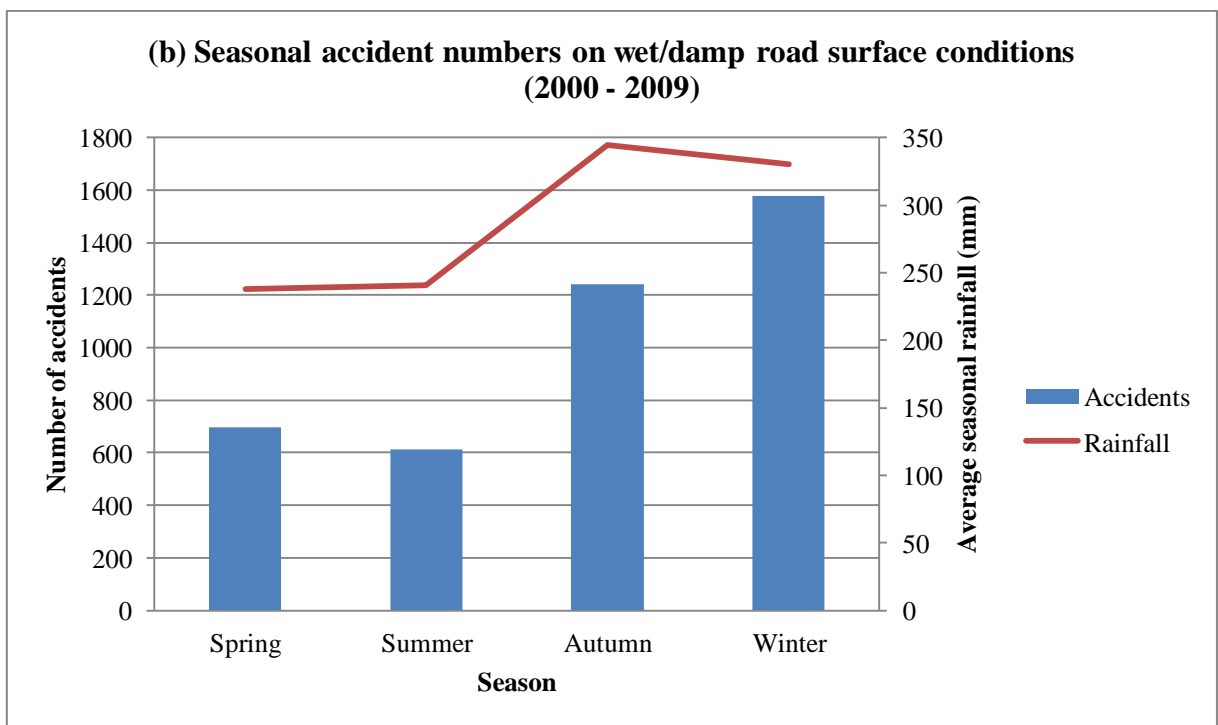
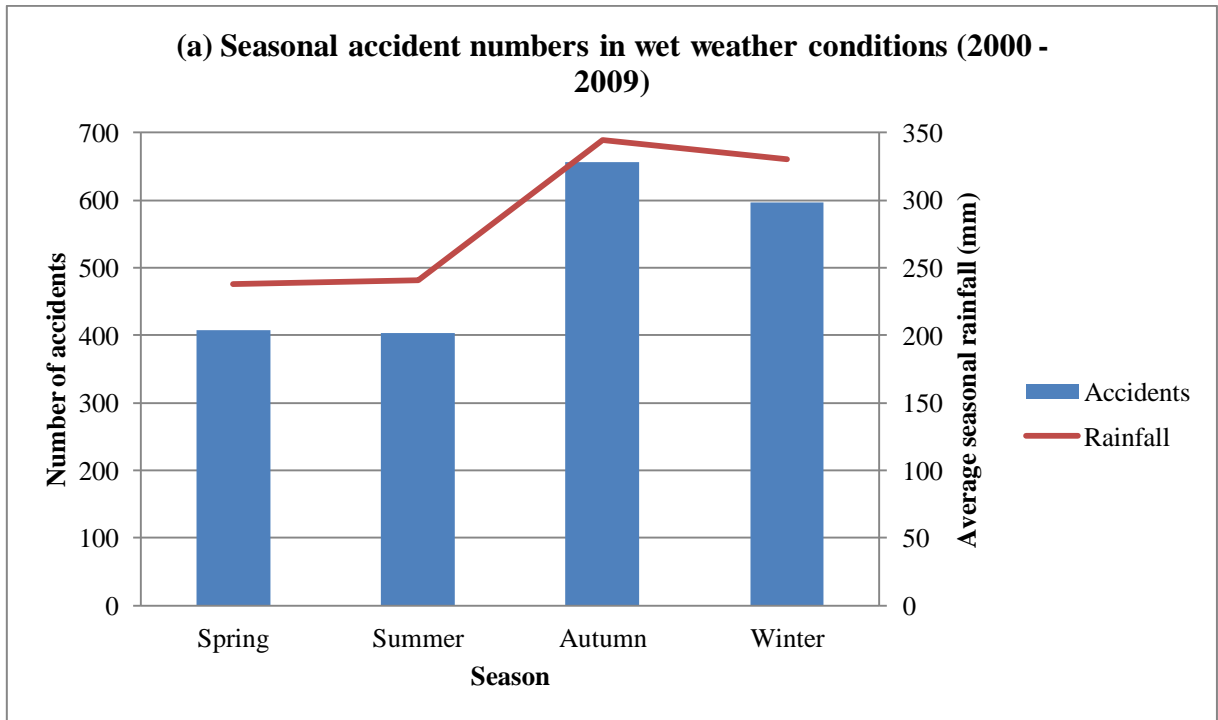


Figure 5.8 Seasonal distribution of traffic accidents and average seasonal rainfall totals (Met Office, 2013) occurring (a) in wet weather conditions, and (b) on wet / damp road surfaces along the M1 and M6 corridor

From the data obtained for accidents during 2008 along this route corridor, it is evident that there is a significant impact on traffic operations in wet weather. This impact is likely to change in future as precipitation patterns and intensities change due to climate change. With the predicted changes in climate, it is expected that there will be more wet weather traffic accidents in winter due to the increase in precipitation during winter months. The predicted increase in accident numbers during winter months, as shown in Figure 5.9, will lead to an increase in the number of journeys which are affected and most likely delayed. It has already been identified that traffic speeds are reduced during precipitation events, and this coupled with increasing numbers of accidents due to wet weather will cause further reductions in both speed and flow especially where accidents cause lane closures or even closures of entire sections of the motorway. These reductions in speed and flow will in turn cause increased congestion not only on the affected motorway but also on roads in the surrounding area. With road use likely to increase in future (Committee on Climate Change and US Transportation, 2008), it is also possible that the number of vehicles and hence journeys affected by road traffic accidents will also increase. The winter increase may be partially offset by a decrease in the number of wet weather accidents occurring during summer months as summer precipitation decreases.

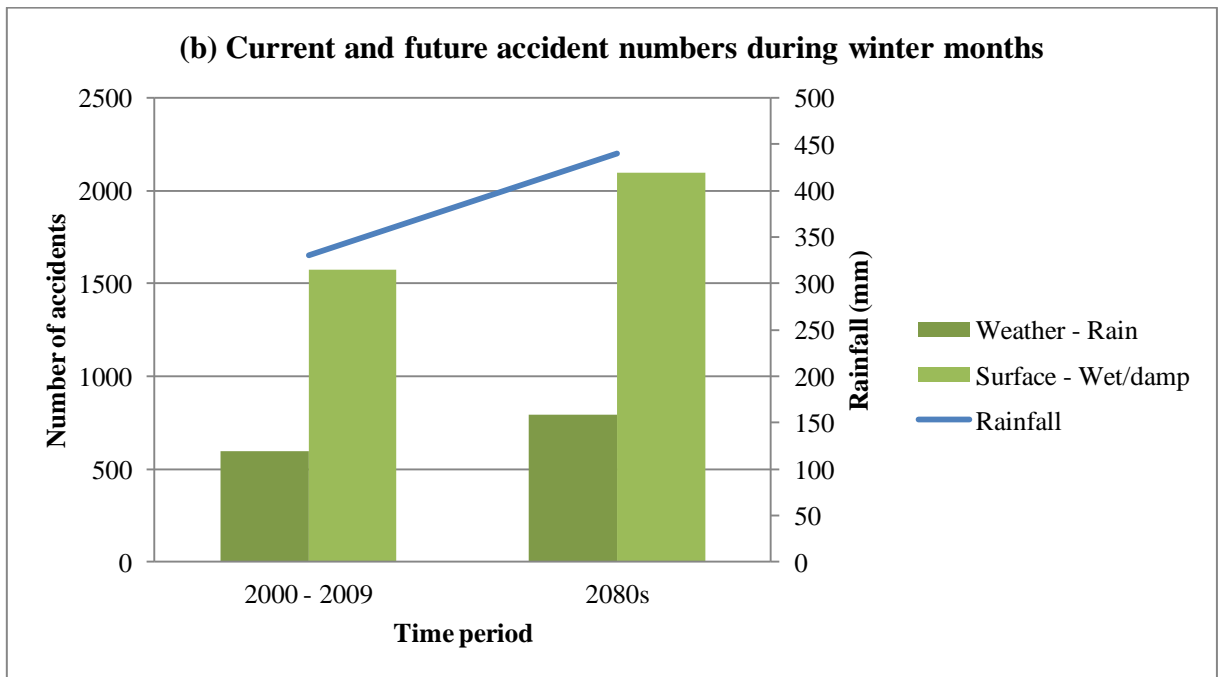
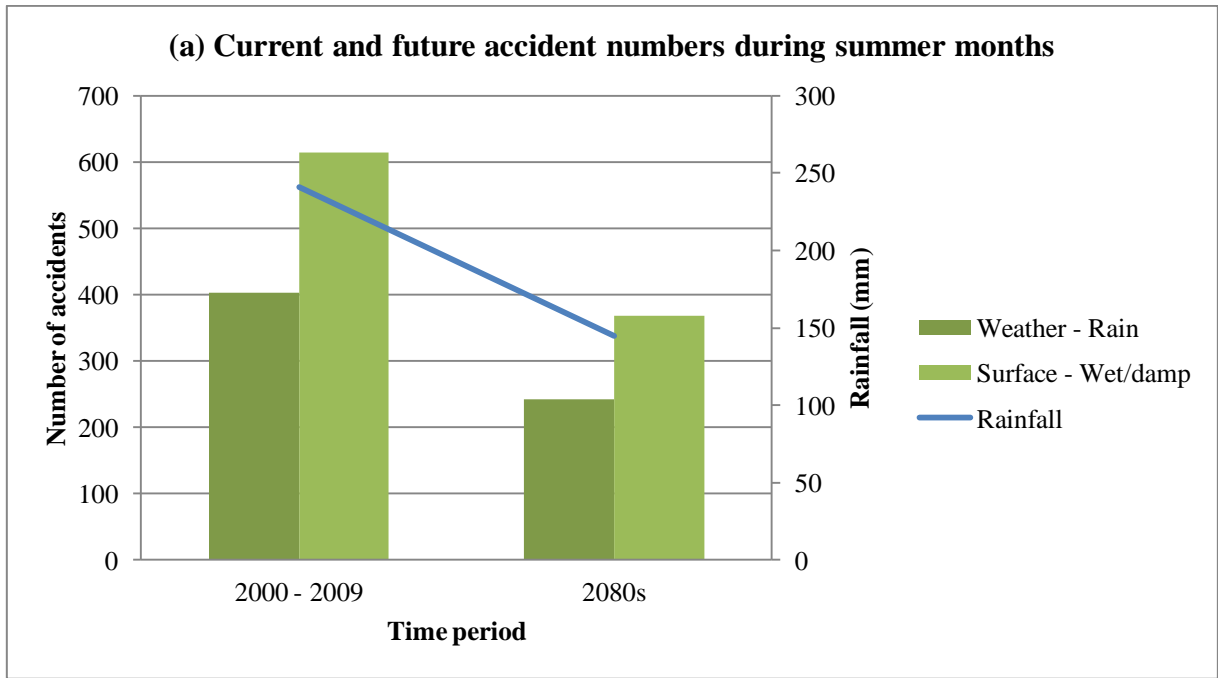


Figure 5.9 Current and potential future accident numbers during wet weather in (a) summer and (b) winter, based on the UKCP09 predicted changes in seasonal precipitation – maximum increase of 33% in winter; maximum decrease of 40% in summer (2000 – 2009 seasonal precipitation totals taken from 1981 – 2010 averages from Met Office, 2013)

These are only simple projections of potential changes in accident numbers due to climate change and of course other factors, such as technology, will affect accident numbers in future. Improvements in driver education may also help in reducing accident numbers and risks as the hazards posed by weather are often misjudged by road users. In 2011, ‘travelling too fast for conditions’ was a contributory factor for around 40% of vehicles involved in reported accidents when the accident reports highlighted that there was bad weather (Department for Transport, 2011). This is a large percentage and could be reduced by raising awareness when driving in adverse weather conditions as well as taking further action to inform drivers of changing weather conditions on their journeys.

5.6 Summary

Road traffic accidents occurring during precipitation events have a significant impact on road network operations causing a reduction in both speed and flow in the majority of cases. These reductions cause delays to journeys and dependent on the severity of the accident, delays can lead to significant failure with some instances where speeds on the motorway do not recover for many hours afterwards. Reductions in speed can occur for up to three hours following an accident in wet weather. This has a sustained effect on road capacity and hence the effective operation of the road network.

In the future, delays will worsen in winter as a result of increasing precipitation, particularly heavy precipitation events, with more accidents leading to more instances of congestion, speed and flow reductions, and road closures. However, summer months are

likely to see a decrease in the number of precipitation related road accidents and in turn less congestion due to decreasing precipitation during these months. Changes to the distribution of traffic throughout the year may also affect accident numbers. At present, traffic volumes peak in August and are lowest in January (Department for Transport, 2013b). Any shift in this distribution will affect accident numbers: for example, an increase in traffic volume in January may lead to a further increase in accident numbers in addition to the increase in accidents occurring due to wet weather, causing further delays and operational problems for the motorway network. The accident predictions presented here are based on seasonal precipitation totals and whilst it is difficult to infer directly what the changes in precipitation may be from seasonal totals, these predictions provide a starting point for understanding how precipitation changes may impact on future accident numbers.

Given the future predictions for precipitation, a number of adaptation measures are required to ensure the increased resistance of the road network in wet weather. Firstly, drainage on the road network is likely to need particular attention. There are already issues with inadequate drainage in a number of locations during convective summer storms (Andreescu & Frost, 1998) and an increase in convective storms due to climate change could see an increase in instances with water lying on the road surface. Water on the road surface is a known cause of traffic accidents (Veith, 1983 in Andreescu & Frost, 1998) and could potentially lead to more accidents in future unless problems with road drainage are addressed. Drainage infrastructure may be able to cope with present precipitation events but with the likely increase in numbers and intensity of future heavy precipitation events due to climate change, drainage will need to be adapted to cope and

ensure the resistance of the road network to such events. Without adaptation to changes in precipitation in future, it is likely that there may be increased instances of surface water on the carriageway where drainage infrastructure fails to cope and with this an associated increase in the risk of accidents due to surface water. It is vital that any problems with drainage are assessed and adaptations made, not only to ensure the network continues to operate effectively but also to ensure the safety of its users.

Weather alone cannot be held responsible for the occurrence of road traffic accidents and so improving driver education, vehicle safety and infrastructure will also play a part in helping to reduce accident numbers. Better utilisation of variable message signs already in place on the motorway network to advise drivers of the adverse weather conditions and action they should take would be highly beneficial (Edwards, 1998). As precipitation is a year round hazard encountered by UK road users, it has a distinctive relationship with traffic accidents. Predicted changes in climate are likely to induce a change in the pattern of accidents occurring during precipitation events. The projected increases in precipitation during winter months are likely to lead to an increase in the number of wet weather traffic accidents and likewise the decrease in summer precipitation may result in a decrease in summer wet weather accidents. Further understanding of the potential impacts of changes in precipitation in future is needed to begin to plan how traffic streams may be managed in future following accidents caused by precipitation and also to allow for mitigation and adaptation procedures to be implemented to try and reduce the impact of a changing climate on road safety.

Chapter 6 – Conclusion

To be able to model the possible impacts of weather on transport in the future, it is important firstly to develop an understanding of how transport is currently affected by weather. Whilst the impacts of a number of weather conditions on all transport modes have been studied to date, previous studies often look at a wide study area or focus on a very small area. Precipitation is a particular hazard for UK drivers. With precipitation regimes across the country varying greatly, there is a pressing need to develop a better understanding of how the road network is affected at a detailed 'junction to junction' scale. This thesis has studied the impact of precipitation on traffic speed, flow, the relationship between speed and flow, and also on traffic accidents and shows that there are vast differences in the magnitude of impacts along a motorway corridor, reinforcing the need for detailed studies to better understand how the network is affected.

6.1 Objective 1

To determine how precipitation currently affects speed on the UK motorway network along the M1 – M6 corridor.

Does one or more key thresholds of failure exist?

The impact of precipitation on speeds on the UK motorway network is not as clear as first hypothesised. A clear negative relationship between the two variables was expected, i.e. as precipitation increases, speed decreases. Having analysed the HATRIS

data available, the key finding is that there is no clearly defined relationship between the two variables for any impact. However, a binary threshold clearly exists at 0 mm h^{-1} – the fastest speeds occur when there is no precipitation and speeds decrease once precipitation occurs. As there is no clear relationship between the two variables at the route level, it is evident that further analysis is needed at a local, junction to junction scale to identify local impacts of precipitation on speed and other traffic parameters. This analysis of the relationship between precipitation and speed at the link level reinforced findings at the route level that there is no clear single factor relationship. However, the finding that speeds decrease during precipitation is reinforced with a reduction in average speeds during precipitation being observed on the majority of links. The magnitude of reduction varies greatly from link to link with the greatest reductions observed in urban areas.

6.2 Objective 2

To identify the impact of precipitation on both speed and flow at a local (junction to junction) scale.

Can traffic on the UK motorway network be approximated to the speed – flow diagram?

Having investigated the impact of precipitation at a local scale, in the majority of cases, speed and flow are reduced when precipitation occurs. The magnitude of reduction for each variable varies from link to link. On creating speed – flow diagrams for each link and comparing these to the speed – flow diagram, it is clear that the relationship

between the two variables is individual to each link. A number of links strongly resemble the speed – flow diagram but there are also cases where there is no resemblance, especially where there is lack of low flow, low speed data. The need for traffic studies at a local scale is reinforced by these findings as the results vary greatly from link to link. As the corridor studied is vital to the economy, an attempt is made to quantify the potential costs of delays due to precipitation due to climate change. With a likely increase in precipitation during winter months, the cost of delays is also likely to increase presenting further challenges in a changing climate unless mitigation and adaptation strategies are applied to the road network such as improved drainage across the network to minimise flooding instances and better utilisation of variable message signs and managed motorways.

6.3 Objective 3

To identify how accidents occurring during wet weather impact on traffic speed and flow at a local scale.

What is the impact on journey travel times? How long does the traffic stream take to recover following precipitation related accidents?

Precipitation is a year round hazard for drivers in the UK and around 15% of all traffic accidents occur in wet weather. The majority have a significant impact on traffic speed and flow with reductions in both parameters following an accident. Speed reductions can last for up to three hours after an accident. The time taken for the network to return to normal after an accident increases significantly in wet weather compared to in dry

weather. The average recovery time for accidents occurring in wet weather or on wet road surfaces is around 50 minutes greater than in dry weather, causing prolonged reductions in traffic flow and increasing the amount of time for which network operations are restricted. Future changes in precipitation patterns due to climate change are likely to lead to changes in wet weather accident numbers. With a predicted decrease in precipitation during summer months, it is likely that the number of wet weather accidents will also decrease. However, this reduction is likely to be offset by an increase in precipitation during winter months and hence an increase in winter wet weather accident numbers.

6.4 FUTURENET

As the FUTURENET project aimed to provide a tool to assess and plan for the resilience of the transport network in future, a modelling framework was created to bring together all aspects of the project. Figure 6.1 shows the modelling concept developed. All aspects of the project were combined to produce a comprehensive model which considered the future shape of the transport network, behaviour of travellers and the relationships between weather and the network. The work presented here forms a small part of the project and its combination with other areas of the project allowed for the development of a comprehensive model to determine the resilience of the transport network in future. This thesis informed the resilience assessment and facilitated the calculation of link travel times, highlighted in Figure 6.1. The calculations of link travel time were based on the speed – flow relationships identified using the HATRIS data. Calculating the travel times at a local scale allowed for identification of any particularly

vulnerable points on the route where precipitation has a strong impact on traffic speeds and hence travel time.

The work undertaken for this thesis does not consider social and technical aspects which will shape the future of the transport network. By the 2050s, there are likely to have been significant developments and improvements to the transport network across the UK. For example changes in the rail network will be evident with the completion of High Speed 2. Whilst FUTURENET has focused on the corridor between London and Glasgow, and in the case of the road network between London and Carlisle, the methodology applied here can be transferred and applied to any transport corridor.

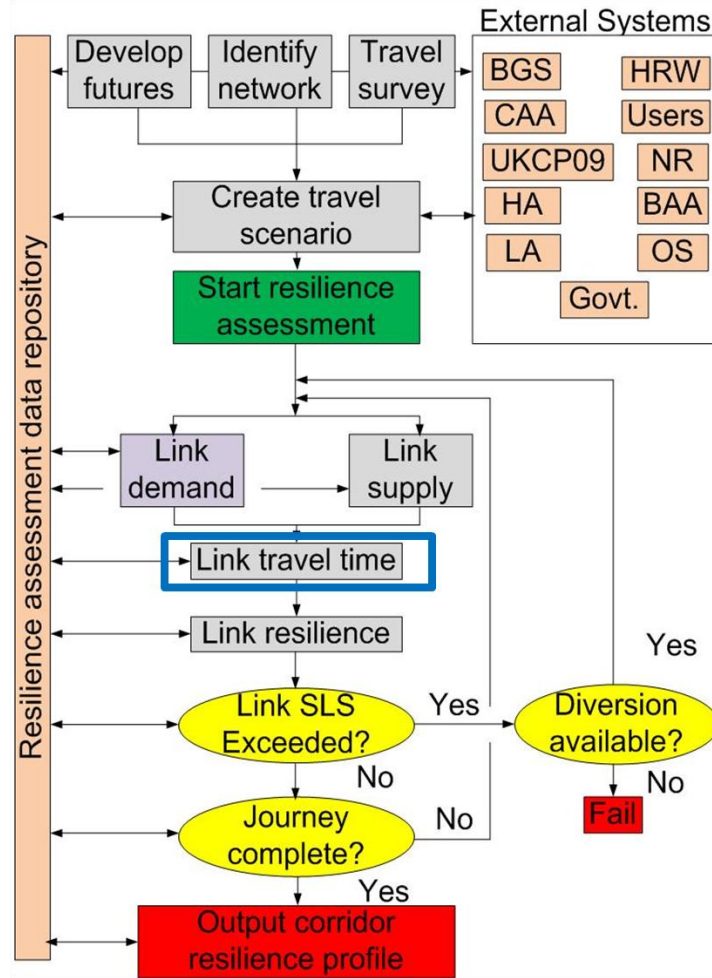


Figure 6.1 FUTURENET modelling concept

The work carried out to complete this thesis has already been used to develop a numerical model to begin quantifying the potential impacts of changes in precipitation on the road network. The model uses the relationships determined in this work, especially the work investigating speed reductions caused by precipitation and the impact on the speed – flow relationship. These findings and weather from the UKCP09 Weather Generator for the 2050s and 2080s are used to calculate potential journey delay times. Calculation of journey times is based primarily on the speed – flow relationships

derived from the HATRIS data (Chapter 5 - Quantifying the Operational Impact of Traffic Accidents during Precipitation on a Motorway Corridor). Using a version of the speed – flow curve for the route takes into account the impact of precipitation on both of these traffic parameters and a corresponding journey time can be calculated depending on the flow on the link and the amount of precipitation. The link journey times are combined for the entire route to provide a total journey delay. Based on the findings of Chapter 3, where there is no precipitation on the route, then there is little or no delay. When precipitation occurs on part of or the entire route then delays occur, ranging from just a few minutes to over an hour. An example southbound journey output from the model is shown in Figure 6.2. There is a steady increase in delay as the journey progresses from Carlisle to London due to the presence of precipitation along the entire route, resulting in an overall journey delay of almost 70 minutes. A further model output is shown in Figure 6.3, for a journey from London to Carlisle where there is initially no precipitation on the route and therefore no delay. Around 100 km into the journey precipitation occurs and as a result, delays are incurred with an overall delay of just under 24 minutes.

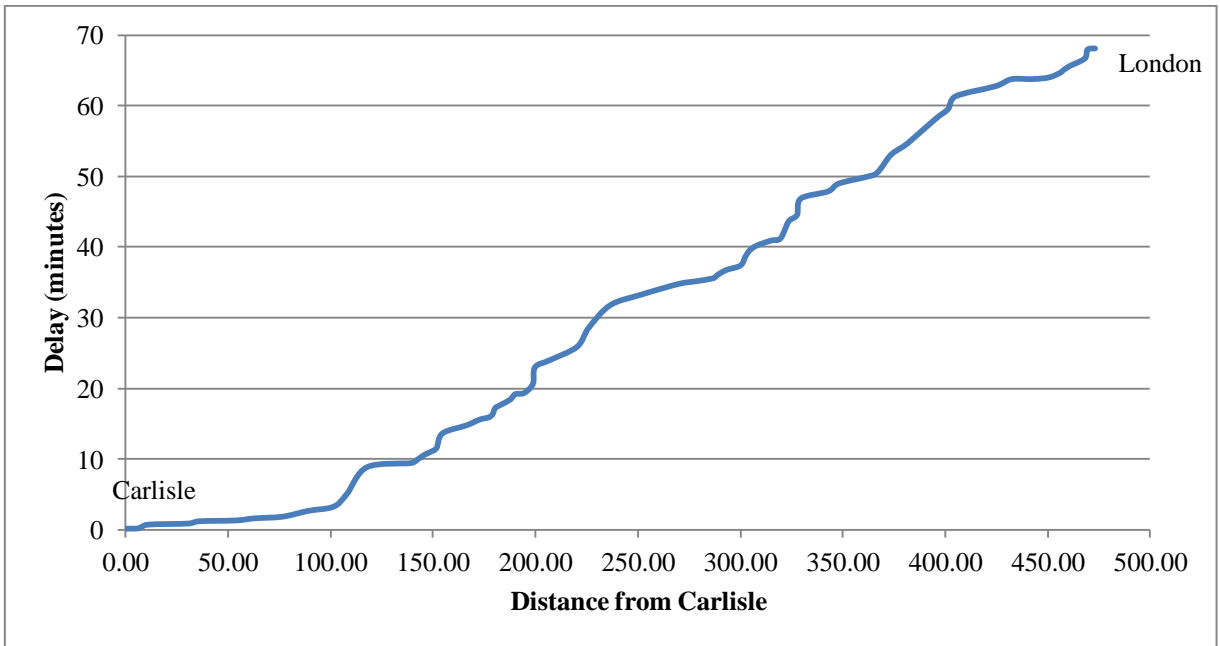


Figure 6.2 Example journey delay output from the FUTURENET resilience model where precipitation occurs along the length of the route

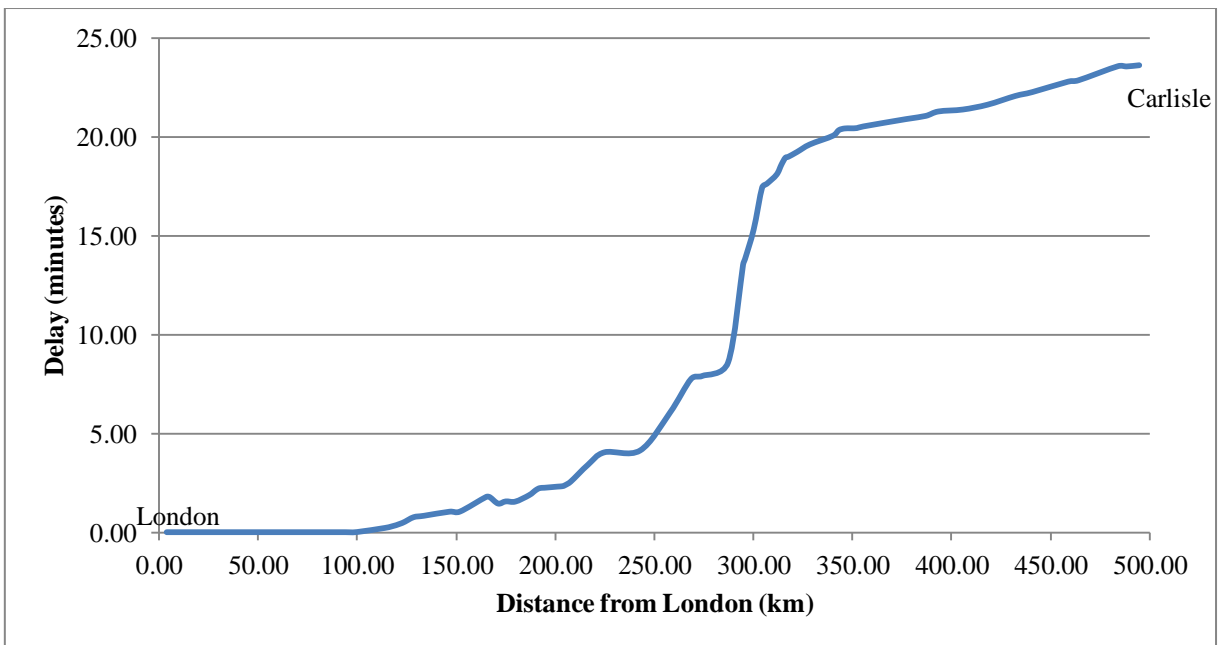


Figure 6.3 Example journey delay output from the FUTURENET resilience model where precipitation starts around 100 km after the start of the journey

6.4.1 FUTURENET Resilience Model Results

The FUTURENET resilience model can produce detailed link by link outputs of delays for a single journey as well as producing overall delays for multiple journeys. To determine how the road network may be affected by climate change in future, the resilience model was run for the summer and winter seasons for the baseline climate, the 2050s (2040 – 2069) and the 2080s (2070 – 2099) using data obtained from the UKCP Weather Generator. The Weather Generator provides 100 runs of the 30 year data and the model was run for one journey per day over the 30 years of all 100 runs. Both medium and high emission scenarios were used to determine how the resilience of the network may vary between the scenarios. A delay threshold of 30 minutes was set and the percentage of journeys exceeding this threshold calculated for each of the model runs completed. The results obtained for the 2050s and 2080s climate change scenarios were compared with those for the baseline climate to identify the impact of precipitation on journey delays in future.

The results showing percentage change in rain related failed journeys can be seen in Figure 6.4. In this instance, the resilience model was run for journeys from Carlisle to London and the failure threshold is 30 minutes. The 10th and 90th percentiles are also shown, indicating the potential range in results obtained from the weather generator data. In winter, there is an increase in failed journeys by the 2050s and a further increase by the 2080s, due to the predicted increase in precipitation in winter months. Although the model predicts that the magnitude of the increase in journeys affected in winter is much greater than the magnitude of reduction in summer, the reduction in summer will

partially offset the increased numbers of failed journeys experienced during the winter months. There is little differentiation between the high and medium emission scenarios in the 2050s. However, by the 2080s there is a considerable difference between the high and medium emissions in winter with the high emissions scenario having a much greater proportion of failed journeys.

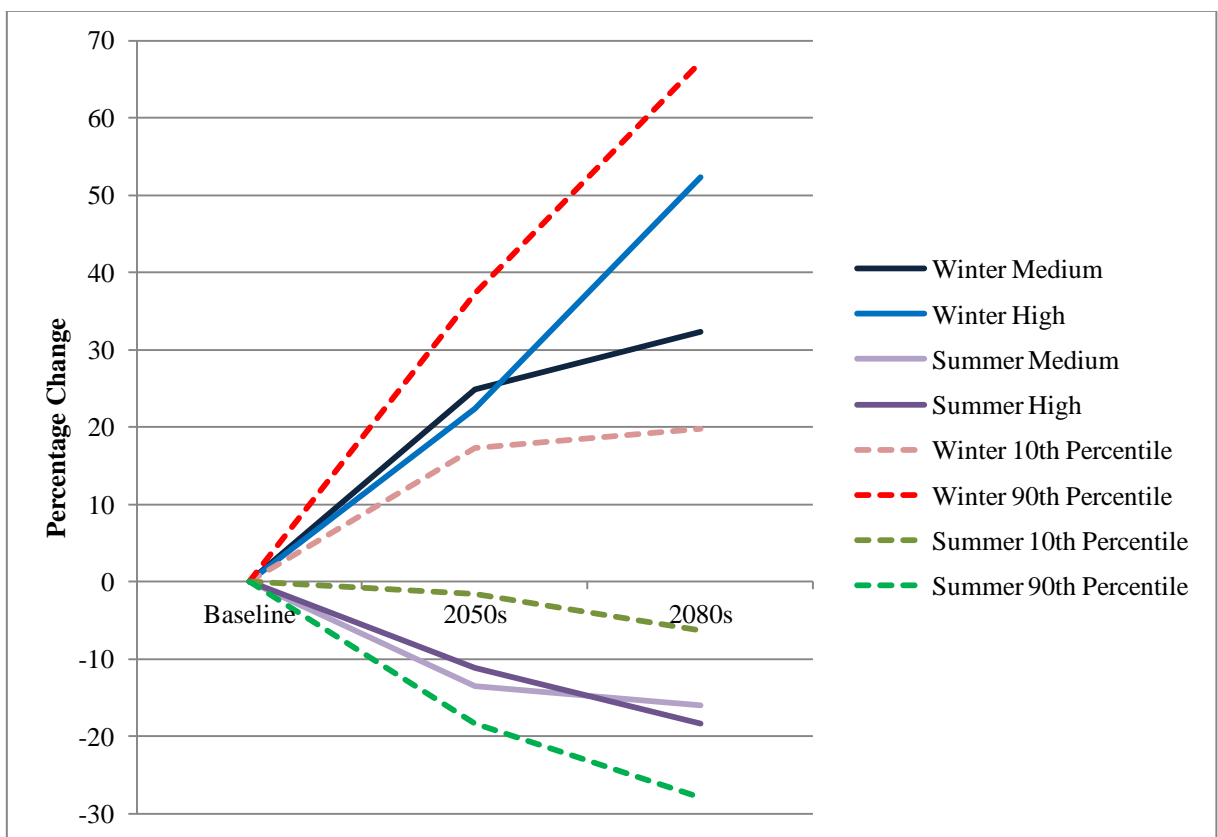


Figure 6.4 FUTURENET resilience model results showing the predicted percentage change of rain – related journey failures in 2050s and 2080s relative to the baseline climate

The results shown here use a failure threshold of 30 minutes' delay for each journey. However, the failure threshold can be altered depending on the requirements of the user, ensuring that the user centric definition of resilience used by the FUTURENET project can be employed in the outputs it produces. For example, a leisure traveller may be satisfied that their journey has not failed until the journey is delayed by more than 45 minutes and the model can be adapted to produce the results for the appropriate end user. The model can also be adapted to use a shorter journey distance within the London to Carlisle corridor and as a result determine the resilience of different sections of the route (e.g. London to Birmingham; Birmingham to Manchester; Manchester to Carlisle).

6.5 Limitations

Over the duration of the FUTURENET project, it became apparent that there are issues with the available data for such studies. There are many instances where data required to determine how transport is affected by climate change do not exist. Where data do exist, it is often inadequate as there tends to be less detail than is required to build a comprehensive picture of the effects of weather on transport. The limitations identified by the FUTURENET project are evident in the data used for this thesis.

There is a notable absence of data which indicates that the motorway is either stationary or operating at a very low speed. When performing speed – flow analysis, there was little data which represented congested traffic, i.e. low speed, low flow. On further

investigation, it was identified that the data set is modified when motorway traffic is at a standstill or when speeds fall below a certain threshold for particular data sources. When the motorway is stationary and as a result there is no speed or flow data for that time, data are infilled using historic data for the link. The consequence of this is that where traffic may have been stationary or moving at a very low speed, it appears that the traffic stream is actually moving at or near to the free flow speed. This issue was particularly apparent when performing accident analysis – often accidents involving multiple vehicles with multiple casualties appeared to have little or no effect on traffic speed and flow. However, the likelihood is that the traffic was stationary or the carriageway was closed and the infilling of historic data caused the true effects of such accidents to be masked.

There is an indicator within the data set which highlights when the data has been infilled. Having examined the data for 2008, it is apparent that 17.62% of speed data and 9.82% of flow data have been infilled. The infilling of data may, as a result, have caused the true relationships between precipitation and the various traffic parameters to have been concealed. For example, extremely low traffic speeds at times of high precipitation may have been omitted and hence the relationship detected between the two variables is not entirely representative. There may in fact be a stronger or more clearly defined relationship if the low speed data were available. Likewise, accident analysis has been impacted with some severe accidents having low recovery times due to data infilling despite multiple vehicles being involved. In reality, it is likely that the recovery time was much higher than the recovery time identified from the HATRIS data. Whilst it is possible to find out where data have been infilled, without knowing

exactly how the infilling has been performed, it is impossible to identify where the low speed, low flow data have been omitted.

Whilst extreme precipitation events are known to have an adverse impact on the road network, the extent of the impact cannot be identified from the data used. During instances of flooding following particularly heavy rainfall, it is expected that sections of road would be closed. However, as there is no way of identifying road closures in the data set, such events cannot be pinpointed. The issue of data being infilled where traffic is stationary is also an issue with respect to extreme precipitation events. If traffic has slowed to a crawl or even come to a standstill during an extreme event (as was the case on motorways around the Midlands in June 2012), the data infilling masks these effects and unfortunately makes it impossible to quantify the extent to which the network was affected.

6.6 Future Research

The analysis completed focuses on a single traffic corridor across England. With data available for the motorway network across England and Wales, further research could apply the methods used here to other corridors to further the understanding of local impacts of precipitation on traffic speed, flow and accidents. Having investigated the relationships between speed and flow at a local scale, it is clear that there is no universal relationship between the two variables which can be applied to links along the route corridor. Future research is needed to characterise the relationships between the

variables and devise improved models to enable better traffic management in future. More HATRIS data are now available, to as recently as February 2013, and using the additional data now available would help to further develop understanding of the impacts of precipitation on traffic parameters across the road network in the UK.

The lack of suitable data sets for use in climate change impact assessment has been identified as a particular limitation at present. The FUTURENET project has already begun to identify the types and quality of data which is needed to carry out comprehensive climate change impact assessments. Future work needs to focus not only on collecting the appropriate data for such assessments but also on utilising the data once collected to develop as complete an assessment as possible to enable the relevant adaptation and mitigation measures to be implemented not only on the road network, but also on other transport modes. Improving the data available in future would also allow for better identification of the impacts of extreme events which is crucial for climate change impact assessment as extreme events are likely to become more frequent in future and hence will need preparing for.

Darkness may be another contributory factor to reductions in both speed and flow during precipitation events. The work presented in this thesis has not distinguished between light and darkness as the aim was to gain an overall picture of the impact of precipitation and so a number of time slices throughout the day were incorporated into the analysis. Future work should investigate how light and dark may also contribute to the relationships derived here, as light conditions are likely to be a contributory factor.

The relationship may extend beyond a simple distinction between day and night lighting conditions, with dusk and dawn also having a potential impact. Previous studies have identified that drivers are more confident in daylight conditions (Wanvik, 2009) and so darkness is likely to affect both speed and flow. In addition, accidents occurring in darkness are consistently more severe than those occurring during daylight hours (Edwards, 1998; Wanvik, 2009) and this in turn is likely to affect traffic operations, though the extent to which they are affected has yet to be quantified.

6.7 Summary

The analysis and results presented in this thesis show that precipitation has a significant impact on the operation of the UK motorway network through reducing speed and flow, and also increasing congestion on the network when accidents occur in wet weather. The varying magnitude of impact on links along the route corridor studied reinforces the need to consider how the road network is affected by weather conditions at a local scale. With some degree of climate change now inevitable, it is important that the relationship between weather and transport is better understood to enable adaptation measures to be implemented to combat the impacts of climate change on all transport modes. The relationships identified here are used to inform a resilience model which takes the first steps towards identifying how the road network may be affected as a result of climate change in future, in particular how journey times will be affected when precipitation occurs. This resilience modelling is essential to enable the network to continue to operate and meet the demands of users in future under all weather conditions, adapting

to a changing climate. Such models will help secure the functioning of what is arguably the economy's most critical asset – whatever the weather.

Appendix A

Hooper E. & Chapman L. (2012) The Impacts of Climate Change on National Road and Rail Networks, in Ryley T. & Chapman L. (Eds) *Transport and Sustainability, Volume 2, Transport and Climate Change*, Emerald, Bingley, pp 105 – 136

I am the primary author of this book chapter which was written in collaboration with Lee Chapman.

Erratum Notice

The errors found in this book chapter should be amended as follows:

Page 105, Methodology/approach

Should read ‘The climate change impacts of increasing summer temperatures, *increasing* winter temperatures...’

Page 122, line 19

Should read ‘London *led* to the...’

Page 131, line 19

Should read ‘able *to* feed our knowledge...’

Page 131, line 29

Should read ‘...Sweden in particular *has* identified...’

Appendix B

Hooper E., Chapman L. & Quinn A (2012) Investigating the impact of precipitation on vehicle speeds on UK motorways, Meteorological Applications, DOI: 10.1002/met.1348

This paper was written to report the results of initial data analysis carried out for this thesis (Chapter 3). I am the primary author. Comments and suggestions were provided by Lee Chapman and Andrew Quinn as my PhD supervisors.

Appendix C

Hooper E., Chapman L. & Quinn A. (2013) The impact of precipitation on speed – flow relationships along a UK motorway corridor, *Theoretical and Applied Climatology*, DOI: 10.1007/s00704-013-0999-5

This paper was written to report the results of speed – flow analysis performed in Chapter 4. I am the primary author. Comments and suggestions were provided by Lee Chapman and Andrew Quinn as my PhD supervisors.

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